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MONTHLY WEATHER REVIEW

VOLUME 82 NUMBER 5

MAY 1954

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The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952

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MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 82
Number 5

MAY 1954

Closed July 15, 1954
Issued August 15, 1954

NORMAL DEGREE DAYS BELOW ANY BASE*

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[Manuscript received May 26, 1954]

ABSTRACT

Heating engineers sometimes have need for normal degree days for bases other than 65° F. Further analysis of the relationship between mean temperature and mean degree days for base 65° F. showed that the form of this relationship is independent of the base. This makes it possible to vary the base to any value and hence to compute degree-day normals for any base from normal temperature. Results are presented for selected stations for bases ranging from 35° to 70° F.

INTRODUCTION

Although 65° F. is by far the most used base below which degree days are measured, other bases have also been occasionally employed [1]. For example 70° is preferred by at least one large user of degree days. Bases lower than 65° are frequently needed in special applications where inside temperatures need only be maintained at values considerably below that required for human comfort. Examples are application to warehouses, automatic substations of various kinds, etc. Unfortunately the lack of statistics for bases other than 65° has discouraged the use of the degree-day concept in many applications where it might have been used to considerable advantage. There are also indications that in some instances other bases between 60° and 70° might be more satisfactory than 65°. It is the purpose of this discussion to extend the method previously developed [2] so that degree days below any base may be readily computed from temperature statistics alone.

THE DISTRIBUTION FOR ANY BASE

In the previous paper [2] on the rational relationship it was shown that the frequency distribution of degree days below base 65° is related to the temperature distribution with the part above 65° cut off or truncated. In the ordinary truncated distribution the values in the cut-off portion are usually ignored or treated in terms of the original scale. This is different from the situation in the degree-day problem, for here all temperatures above 65° have degree-day values of zero. Hence as shown in [2] the degree-day distribution is a mixture of the temperature distribution on a scale measured downward from 65° with the zeros occurring when the temperature is above 65°. If F is the cumulative distribution of the *daily* average temperature t, D the degree days below 65°, and p and q the probabilities of temperatures above and below 65°, respectively; then the distribution function of degree days may be expressed in the form (see [2]):

$$G(D|D\geq 0)=p+qF(65-t|t\leq 65). \tag{1}$$

Since the development leading to equation (1) is clearly independent of the degree-day base because 65 enters only as a parameter, the general base b may be substituted for 65 giving

$$G(D|D\geq 0)=p+qF(b-t|t\leq b). \tag{2}$$

This is the distribution of degree days to any base.

THE GENERAL RELATIONSHIP OF DEGREE DAYS TO TEMPERATURE

Since there can be no parameters in degree-day statistics which are not in the distribution of degree days,

*Presented at the 128th National Meeting of the American Meteorological Society, Baltimore, Md., April 30, 1954.

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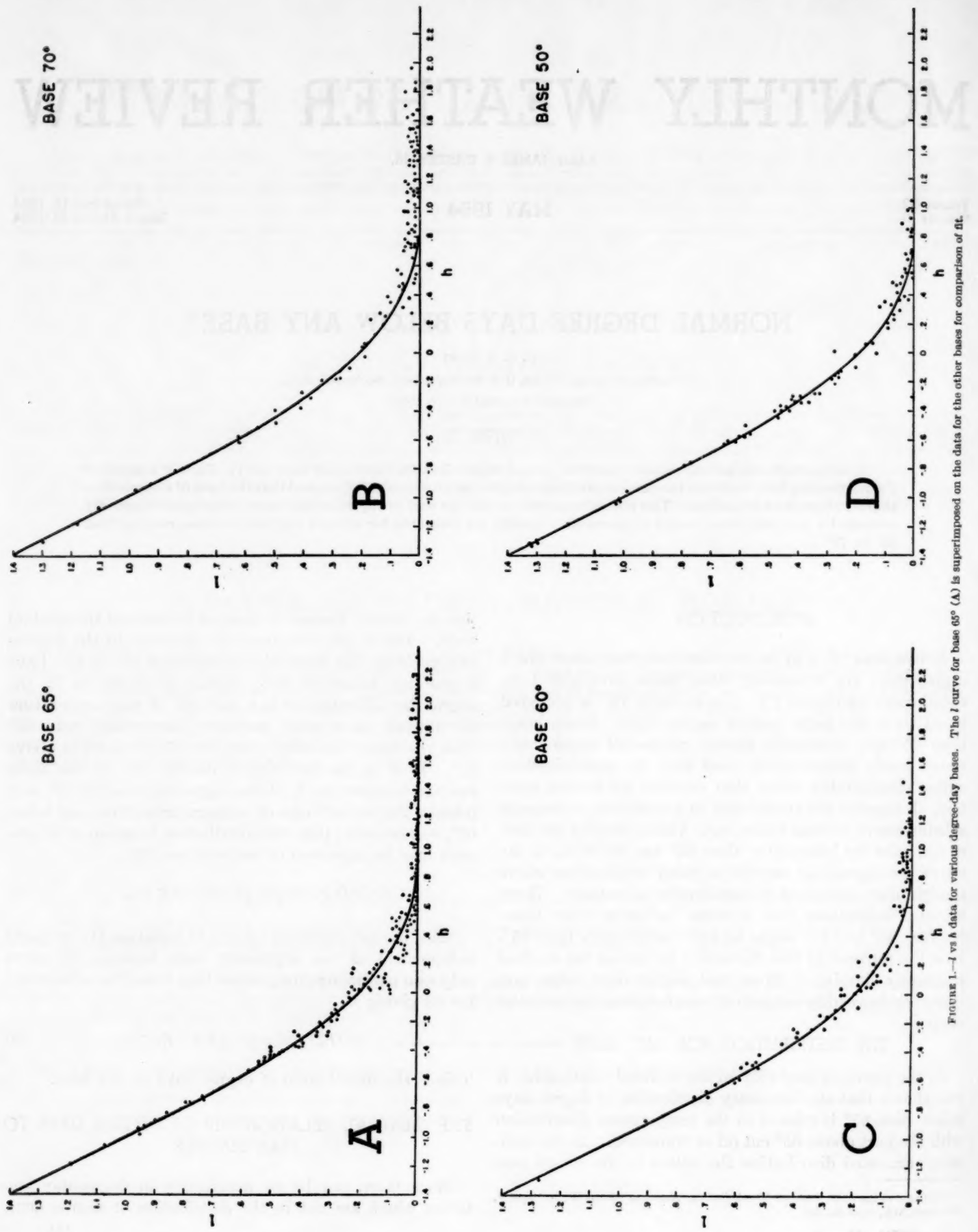

FIGURE 1.—l vs h data for various degree-day bases. The l curve for base 65° (A) is superimposed on the data for the other bases for comparison of fit.

the derivation of the relationship of mean degree days to mean temperature will be identical with the development for 65° in reference [2], except that b will be substituted for 65. Hence the rational relationship becomes

$$E(D)=q[b-E(t)+\lambda\sigma]. \tag{3}$$

where E is the population mean degree day, λ is the ratio of the ordinate of the frequency curve at b to the area under this curve below b, and σ is the standard deviation of t. Rearrangement of equation (3) immediately gives

$$\lambda-\frac{E(D)}{\sigma}\frac{(1-q)}{q}=\frac{E(D)-b+E(t)}{\sigma}. \tag{4}$$

This relationship is for a single day, and since σ for each day is not available, it must be adjusted for use with monthly data. It was shown in reference [2] that the monthly standard deviation σ_m is proportional to $\sigma/\sqrt{N}$ for an average day during a month with N days. Hence substituting $\sqrt{N}\sigma_m$ for σ and l for the left member in equation (4) gives the required empirical generalization

$$l=\frac{E(D)-b+E(t)}{\sqrt{N}\sigma_m}. \tag{5}$$

$E(D)$, $E(t)$, and σ_m are population values which are estimated by the statistics $\bar{D}$, $\bar{t}$, and s_m. Substituting these in equation (5) gives

$$l=\frac{\bar{D}-b+\bar{t}}{\sqrt{N}s_m}. \tag{6}$$

l is a function only of the parameters in the left member of equation (4) which are in turn functions of σ and $E(t)$ and hence of $\sqrt{N}s_m$ and $\bar{t}$. Therefore l is a function of the normalized value of b, $h=(b-\bar{t})/\sqrt{N}s_m$. It is to be expected if the theory is general, that the l curves will be identical for all bases. Figures 1B, C, D show the original l-curve obtained for the 65° base superimposed on l vs h data for three different bases. These data were obtained from all months with degree days at 12 stations well distributed over the United States. They may be compared to figure 1A for 65° data. There is clearly little difference in the fit of the l-curve among the data for the various bases and therefore the theory seems to be general. In an application to automatic substations, bases were required down to 0°. For this purpose the theory was checked for 30° and 0° bases and found to be as good as shown for the higher bases in the figures. The l table (table 1 of reference [2]) may therefore be used for all bases. The computation formula for monthly degree-day means to any base is now easily obtained by solving equation (6) giving

$$N\bar{D}=N(b-\bar{t}+l\sqrt{N}s_m). \tag{7}$$

EXAMPLES

From a manuscript set of charts of monthly standard deviation we find s_m for April at Minneapolis to be 4.0°. The normal temperature for April is 46.0°. Hence for base 50°, $h=(50-46.0)/(5.477)(4.0)=0.18$. From table 1 of reference [2], l is found to be 0.11. Using equation (7) gives

$$30\bar{D}=30[50-46.0+(0.11)(5.477)(4.0)]=192.$$

This is the normal degree days to base 50° for April at Minneapolis.

In table 1, the tabulation for selected cities in the United States and Canada gives an idea how the degree-day normals vary for several bases.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Mr. Maurice Kasinoff for performing all computations in connection with the theoretical work and to Mr. Daniel Harton for developing the necessary tabulating machine methods for the preparation of tabulations of degree-day normals.

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1. Clifford Strock and C. H. B. Hotchkiss, *Degree-Day Handbook*, Industrial Press, New York, 2d edition 1937, pp. 132–134.
2. H. C. S. Thom, "The Rational Relationship between Heating Degree Days and Temperature," *Monthly Weather Review*, vol. 82, No. 9, Jan. 1954, pp. 1–6.

TABLE 1.—*Degree-day normals for several bases for selected cities in the United States and Canada*

Base	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
SAINT LOUIS, MO., CITY OFFICE													
70° F	0	9	90	318	720	1,048	1,138	932	766	405	175	38	5,639
65	0	0	38	202	570	893	983	792	620	270	94	7	4,469
60	0	0	0	119	426	738	828	652	483	156	41	0	3,443
55	0	0	0	56	292	591	683	520	365	77	6	0	2,590
50	0	0	0	19	176	452	547	394	255	29	0	0	1,872
45	0	0	0	0	93	321	422	283	174	7	0	0	1,300
40	0	0	0	0	38	221	306	187	110	0	0	0	862
35	0	0	0	0	5	137	220	119	56	0	0	0	537

TABLE 1.—*Degree-day normals for several bases for selected cities in the United States and Canada*—Continued

Base	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
NEW YORK, N. Y., CITY OFFICE													
70° F.	0	31	117	403	711	1,063	1,150	1,044	908	606	289	68	6,390
65	0	0	39	263	561	908	995	904	753	456	153	18	5,050
60	0	0	5	148	411	753	840	764	598	311	63	0	3,893
55	0	0	0	68	269	598	685	624	458	183	10	0	2,895
50	0	0	0	18	144	443	538	484	325	90	0	0	2,042
45	0	0	0	0	60	305	406	356	213	29	0	0	1,369
40	0	0	0	0	17	183	282	239	131	0	0	0	852
35	0	0	0	0	0	100	189	145	70	0	0	0	504
CLEVELAND, OHIO, AIRPORT													
70° F.	27	53	164	484	849	1,212	1,287	1,159	1,029	681	349	102	7,396
65	0	10	75	340	699	1,057	1,132	1,019	874	531	223	46	6,006
60	0	0	20	212	549	902	977	879	719	386	125	0	4,769
55	0	0	0	118	404	747	822	739	582	258	55	0	3,725
50	0	0	0	51	270	592	676	599	446	152	20	0	2,806
45	0	0	0	12	157	452	530	466	327	77	0	0	2,021
40	0	0	0	0	80	318	402	346	227	25	0	0	1,398
35	0	0	0	0	30	207	293	232	155	5	0	0	922
PHILADELPHIA, PA., CITY OFFICE													
70° F.	0	13	94	357	666	1,011	1,088	977	822	519	207	38	5,792
65	0	0	33	219	516	856	933	837	667	369	93	0	4,523
60	0	0	0	114	366	701	778	697	518	232	29	0	3,435
55	0	0	0	44	224	546	623	557	377	120	0	0	2,491
50	0	0	0	6	111	396	484	423	257	47	0	0	1,724
45	0	0	0	0	37	257	353	294	157	8	0	0	1,106
40	0	0	0	0	0	150	246	188	92	0	0	0	676
35	0	0	0	0	0	70	154	104	40	0	0	0	368
PITTSBURGH, PA., CITY OFFICE													
70° F.	7	33	125	437	762	1,079	1,147	1,019	880	546	249	56	6,340
65	0	0	56	298	612	924	992	879	735	402	137	13	5,048
60	0	0	16	175	462	769	837	739	590	268	60	0	3,916
55	0	0	0	90	322	614	692	599	465	163	16	0	2,961
50	0	0	0	37	198	473	556	474	349	86	0	0	2,173
45	0	0	0	5	104	340	430	356	243	36	0	0	1,514
40	0	0	0	0	45	221	314	246	167	0	0	0	993
35	0	0	0	0	8	139	226	165	110	0	0	0	648
WASHINGTON, D. C., CITY OFFICE													
70° F.	0	10	90	365	660	986	1,039	910	753	459	175	24	5,471
65	0	0	32	231	510	831	884	770	606	314	80	0	4,258
60	0	0	7	127	360	676	729	630	459	187	24	0	3,199
55	0	0	0	55	222	521	582	496	336	92	0	0	2,304
50	0	0	0	14	113	371	454	369	228	34	0	0	1,583
45	0	0	0	0	41	244	325	255	145	0	0	0	1,010
40	0	0	0	0	0	139	232	159	78	0	0	0	608
35	0	0	0	0	0	67	147	89	42	0	0	0	345
CHICAGO, ILL., AIRPORT													
70° F.	24	43	171	493	915	1,302	1,398	1,193	1,023	657	353	119	7,691
65	0	0	90	350	765	1,147	1,243	1,053	868	507	229	58	6,310
60	0	0	34	224	615	992	1,088	913	713	368	131	14	5,092
55	0	0	7	128	465	837	933	773	576	241	69	0	4,029
50	0	0	0	61	332	682	778	633	439	141	25	0	3,091
45	0	0	0	17	211	544	632	500	320	69	0	0	2,293
40	0	0	0	0	119	406	495	374	228	20	0	0	1,642
35	0	0	0	0	55	293	367	263	144	0	0	0	1,122
BOSTON, MASS., AIRPORT													
70° F.	19	52	181	465	768	1,153	1,268	1,142	1,004	684	378	120	7,234
65	0	7	77	315	618	998	1,113	1,002	839	534	236	42	5,791
60	0	0	16	188	468	843	958	862	694	384	118	5	4,536
55	0	0	0	89	323	688	803	722	539	242	46	0	3,452
50	0	0	0	31	196	533	648	582	398	129	0	0	2,517
45	0	0	0	7	96	391	500	448	278	53	0	0	1,773
40	0	0	0	0	38	260	368	320	171	10	0	0	1,167
35	0	0	0	0	0	155	250	209	99	0	0	0	713
DETROIT, MICH., CITY AIRPORT													
70° F.	28	50	193	530	897	1,256	1,358	1,212	1,082	708	384	128	7,826
65	0	8	96	381	747	1,101	1,203	1,072	927	558	251	60	6,404
60	0	0	35	249	597	946	1,048	932	772	414	145	17	5,155
55	0	0	5	145	447	791	893	792	626	281	73	0	4,053
50	0	0	0	75	307	636	738	652	488	171	23	0	3,090
45	0	0	0	23	182	487	591	519	360	90	0	0	2,252
40	0	0	0	0	96	345	452	386	258	38	0	0	1,575
35	0	0	0	0	34	229	321	272	164	0	0	0	1,020

TABLE 1.—*Degree-day normals for several bases for selected cities in the United States and Canada*—Continued

Base	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
MINNEAPOLIS, MINN., AIRPORT													
70° F	49	70	262	608	1,110	1,569	1,717	1,450	1,212	720	378	145	9,290
65	8	18	157	459	960	1,414	1,562	1,310	1,057	570	259	80	7,854
60	0	0	79	332	810	1,259	1,407	1,170	902	433	170	28	6,590
55	0	0	30	212	660	1,104	1,252	1,030	747	303	95	5	5,438
50	0	0	8	126	517	949	1,097	890	601	192	41	0	4,421
45	0	0	0	67	381	794	942	750	464	115	9	0	3,522
40	0	0	0	23	258	648	799	620	345	57	0	0	2,750
35	0	0	0	6	164	511	655	498	244	18	0	0	2,096
CALGARY, ALBERTA, CANADA													
65° F	136	175	420	713	1,110	1,426	1,612	1,344	1,209	750	465	279	9,639
60	55	75	285	558	960	1,271	1,457	1,204	1,054	600	320	155	7,994
55	12	20	166	403	810	1,116	1,302	1,064	899	450	189	72	6,503
50	0	0	87	269	669	961	1,147	924	744	317	92	24	5,234
45	0	0	29	150	528	818	992	784	597	202	33	0	4,133
40	0	0	6	73	405	687	850	654	458	109	0	0	3,242
35	0	0	0	26	300	556	720	533	327	51	0	0	2,513
EDMONTON, ALBERTA, CANADA													
65° F	133	209	450	744	1,200	1,612	1,829	1,512	1,302	750	434	222	10,397
60	53	106	316	589	1,050	1,457	1,674	1,372	1,147	600	289	111	8,764
55	9	44	194	448	912	1,302	1,519	1,232	992	457	167	40	7,316
50	0	5	103	313	775	1,163	1,364	1,092	837	326	80	5	6,063
45	0	0	45	200	637	1,023	1,209	952	691	216	27	0	5,000
40	0	0	9	121	524	884	1,069	823	545	125	0	0	4,100
35	0	0	0	63	411	744	928	694	417	67	0	0	3,324
VANCOUVER, BRITISH COLUMBIA, CANADA													
65° F	78	91	243	465	660	806	899	728	682	510	341	175	5,678
60	16	21	116	314	510	651	744	588	527	360	208	78	4,133
55	0	0	39	181	360	496	589	454	372	222	100	27	2,840
50	0	0	0	82	228	346	448	326	230	113	36	0	1,809
45	0	0	0	26	120	216	313	215	118	41	6	0	1,055
40	0	0	0	0	53	116	200	129	45	0	0	0	543
35	0	0	0	0	8	46	121	66	0	0	0	0	241
WINNIPEG, MANITOBA, CANADA													
65° F	68	100	341	744	1,290	1,829	2,108	1,764	1,519	810	409	157	11,139
60	18	36	219	589	1,140	1,674	1,953	1,624	1,364	660	279	80	9,636
55	0	6	125	449	990	1,519	1,798	1,484	1,209	517	174	36	8,307
50	0	0	59	322	840	1,364	1,643	1,344	1,054	381	93	0	7,100
45	0	0	15	211	700	1,209	1,488	1,204	899	258	38	0	6,022
40	0	0	0	128	570	1,054	1,333	1,064	755	164	7	0	5,075
35	0	0	0	68	439	899	1,178	924	610	96	0	0	4,214
SASKATOON, SASKATCHEWAN, CANADA													
65° F	95	136	426	806	1,290	1,798	2,046	1,736	1,488	840	448	192	11,301
60	35	55	292	651	1,140	1,643	1,891	1,596	1,393	690	313	100	9,739
55	5	12	176	503	990	1,488	1,736	1,456	1,178	548	200	45	8,337
50	0	0	93	370	852	1,333	1,581	1,316	1,023	423	121	5	7,117
45	0	0	38	251	713	1,178	1,426	1,176	880	306	63	0	6,031
40	0	0	5	154	587	1,023	1,271	1,049	737	205	18	0	5,049
35	0	0	0	86	472	880	1,132	909	606	129	0	0	2,214
DAWSON, YUKON TERRITORY, CANADA													
65° F	181	310	690	1,209	1,920	2,449	2,666	2,156	1,891	1,080	589	254	15,396
60	82	175	540	1,054	1,770	2,294	2,511	2,016	1,736	930	434	141	13,683
55	26	75	390	899	1,620	2,139	2,356	1,876	1,581	780	289	64	12,095
50	0	20	255	744	1,470	1,984	2,201	1,736	1,426	638	167	20	10,661
45	0	0	144	598	1,320	1,829	2,046	1,596	1,271	497	80	0	9,381
40	0	0	68	460	1,170	1,674	1,891	1,456	1,116	373	27	0	8,235
35	0	0	22	339	1,020	1,519	1,736	1,316	961	266	0	0	7,179

STATISTICS ON THE MOVEMENT AND DEEPENING OF CYCLONES IN THE MIDDLE WEST

John C. Hurley

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[Manuscript received April 15, 1953; revised April 7, 1954]

ABSTRACT

The inter-relations of intensity, speed, and direction of movement of cyclones in the central United States are investigated. Evidence is developed concerning the validity of several forecasting rules relating to the movement of cyclones.

INTRODUCTION

The objective of this investigation was to evaluate some of the forecasting rules which relate to the interdependence of cyclone intensity, direction of movement, and speed. Particular attention was given to rules concerning the tendency of cyclones to intensify when moving to the left of a normal course [1], and the corollary tendency to decrease or fill when moving to the south or southeast. Although rules such as these are not explicitly utilized in present-day forecasting to the same extent as formerly, they nonetheless influence the forecast from the subjective side since the experience and empirical knowledge of the forecaster tend to be formulated in such terms. An objective assessment of these rules therefore appears desirable.

The plan of attack consisted of correlating the *direction* taken by various cyclones with: (1) the initial pressure of the cyclone center; (2) the 12-hour change in central pressure; and, (3) the distance moved in the subsequent 12 hours. In addition, the *distance* cyclones moved in 12 hours was compared with: (4) the 12-hour change in central pressure and, (5) the initial pressure of the low center.

The procedure for obtaining these data was relatively free of bias since the source material, storm tracks from the *Monthly Weather Review* from 1920 to 1929, inclusive, gives not only the storm track but the central pressure at 12-hour intervals. For items (1) to (3) direction was divided into octants, the first extending from 1° to 45°, the second from 46° to 90°, and so on. The pressure given at the beginning of each 12-hour track, the distance moved in the subsequent 12 hours, and the change in pressure during the 12 hours were each tabulated in appropriate direction categories.

For item (4) a similar procedure was followed with pressure change ordered into nine categories, the central category representing zero change and those on either side increasing by steps of .10 inch in 12 hours with the first and last category reserved for changes in excess of .30 inch, minus and plus respectively. The same method was used for item (5) with the central pressure of the cyclones ordered into six categories, the first including all those less than 29.20 inches, and the last those above 29.99, with the four intervening categories each subtending .20 inch.

The data were tabulated separately for summer, winter, and all year. Summer in this study was arbitrarily defined as the five months extending from May through September and winter the period from November through March. October and April were omitted from both seasons (but, of course, are included in the all year data) due to the considerable range of latitude within the defined area. Along the Gulf of Mexico these months are more nearly characteristic of the summer season while at the Canadian border they would usually be included in the colder half of the year. A division into the four standard seasons would have been preferable but the data were not sufficiently numerous to support the additional subdivisions.

The decade of the 1920's was chosen as the base for this study for two reasons. First, larger scale charts were used prior to 1930 for showing the cyclone tracks, permitting greater accuracy in scaling off the distances; and second, these charts give the central pressure of each cyclone for both 0700 and 1900 CST while the charts since 1930 give only the 0700 CST pressure. The 12-hour interval is, of course, preferable where the relation of direction to other variables is the subject of interest. The choice of this decade entails some loss of accuracy as compared with more recent years due to the sparser station network of that time.

The area studied was restricted to that portion of the central United States bounded by the 85th and 100th meridians between the parallels of 30° and 50° N. None of the ground within this area exceeds 3,000 feet in eleva-

tion so that sea level pressures may be used with reasonable confidence. Many of the poorly defined Lows in the lee of the Rockies are also excluded by this choice. All of the tracks within this area were included in the summary with the exception of a few for which the central pressure of the cyclone was not recorded. One hurricane which moved into the area in 1926 and filled very rapidly was also excluded. A total of 2,177 12-hour tracks was summarized. Although the *Monthly Weather Review* charts show the cyclone tracks as smooth curves, the 12-hour segments were, for this study, assumed to be straight lines.

The source material and the methods of extracting the data impair the accuracy of the results in some respects. The monthly cyclone tracks are published on relatively small-scale charts so that distances had to be scaled off to the nearest ten miles. The circles used to show the location of the centers were never drawn as overlapping and were of such size that the shortest 12-hour movement that could be shown, measuring from center to center, was approximately 60 miles. A third element of error arose in determining the direction of the tracks. The octants into which direction was divided were found by bisecting the angles formed by meridians and parallels by straight lines. On a chart of conic section where latitude is shown as curved lines, a straight line bisector does not define true octants. For the range of distances included in this study the error attributable to this cause is not much greater than that involved in locating the center of a cyclone and it affects only those tracks along the boundary of the octants.

CENTRAL PRESSURE VS. DIRECTION OF MOVEMENT

Figure 1 shows the average pressure of cyclones plotted against the subsequent direction of motion. The curves for winter and for the year as a whole both show progressively higher mean central pressures corresponding to the shift in direction from north-northeast to south-southeast. In winter, for example, the average pressure for all storms that moved north-northeast in the subsequent 12 hours was 29.55 inches, the average for those moving east-northeast was 29.66, those moving east-southeast 29.68, and those directed south-southeast averaged out at 29.73 inches. The graph for the year as a whole has the same trend over this range of direction but with a somewhat smaller and more uniform increase in pressure corresponding to the increasing southward deflection of the cyclone tracks. This trend is supported by so considerable a mass of data that it can hardly be dismissed as coincidental even though those summer storms moving north-northeast fail to fit the general picture. Curves for winter conditions were omitted for the octants SSW through NNW in figure 1 (and also in figs. 2, 3, 4, and 5) as there were a total of only four cases showing movement to the west. Less than three percent of the data for the entire decade fell within these octants, so not much weight can be assigned even to those curves that are shown for westward-moving storms.

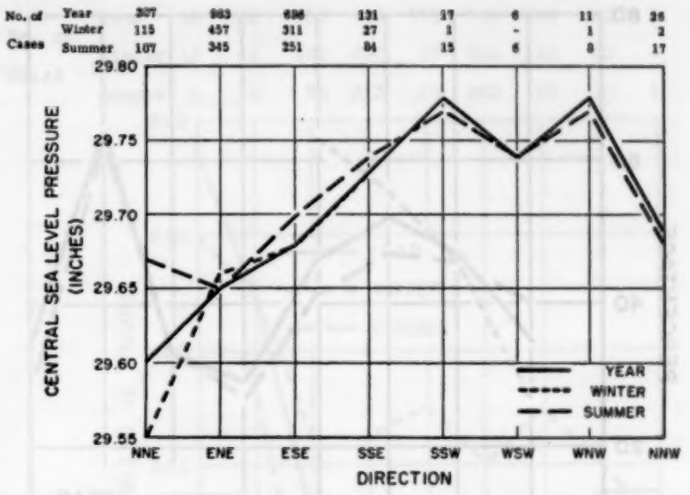

FIGURE 1.—Mean central sea level pressure of cyclones plotted against direction toward which they moved in subsequent 12 hours. Number of cases falling into each octant is shown across top of graph. Summer includes May through September; winter, November through March.

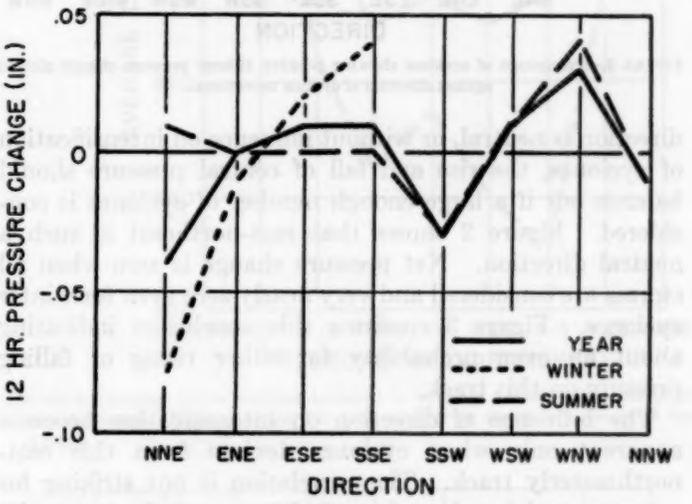

FIGURE 2.—Mean net change in central pressure in 12 hours plotted against direction of movement of cyclones. The number of cases for each direction is the same as in figure 1.

It will be noted from the frequency table accompanying figure 1 that storms moving east-northeast represent a high percentage of the total. This direction, which may be taken as approximately the mean, or normal, direction for cyclones included in this study, shows very little seasonal variation in central pressure. Those storms moving to the left of this course are of greater than average intensity, assuming that central pressure is an index of intensity, while those of less intensity are deflected to the south with the greatest deflection corresponding to the least intensity.

12-HOUR PRESSURE CHANGE VS. DIRECTION OF MOVEMENT

Figure 2 shows the mean net change of central pressure for 12 hours plotted against direction of cyclone movement. The mean net change for a given direction is the algebraic mean of *all* cases in that direction category. Where

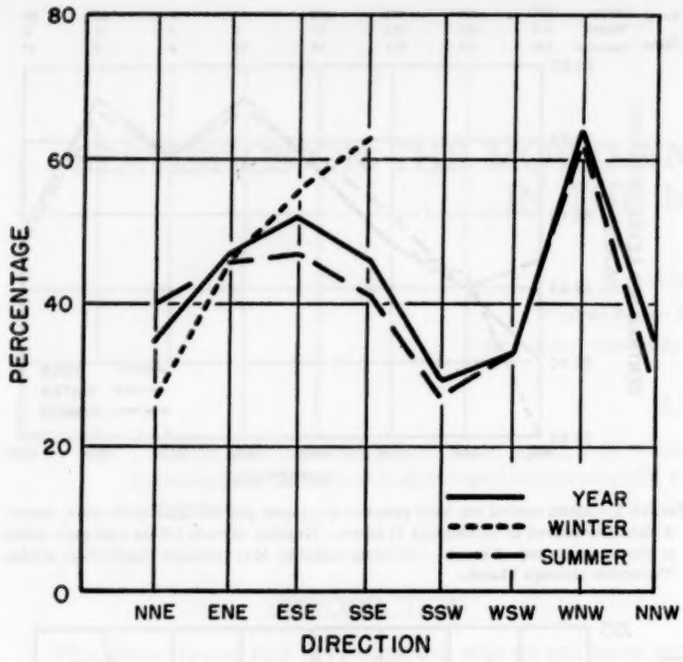

FIGURE 3.—Percentage of cyclones showing positive 12-hour pressure change plotted against direction of cyclone movement.

direction is neutral, or without influence on intensification of cyclones, the rise and fall of central pressure should balance out if a large enough number of cyclones is considered. Figure 2 shows that east-northeast is such a neutral direction. Net pressure change is zero when all storms are considered and very nearly zero even for winter cyclones. Figure 3 confirms this conclusion indicating about an even probability for either rising or falling pressure on this track.

The influence of direction on intensification becomes apparent only when cyclones deviate from this east-northeasterly track. The correlation is not striking for summer cyclones but the consistency of the curve for winter conditions in figure 2 is noteworthy. For storms moving north-northeast, 69 percent showed falling pressure with an average decrease of .15 inch in 12 hours. The average net change in pressure for all storms moving in this direction was −.08 inch in 12 hours. Saucier [4] found a similar relation between pressure change and direction in his study of Texas cyclones.

The winter cyclones moving south of east showed an increasing tendency for rising central pressure culminating in a 12-hour average net rise of .04 inch for those moving south-southeast; 63 percent of the 27 cyclones sharing this direction were characterized by rising central pressure.

The similarity of the curves for figures 1 and 2 is, of course, not accidental since the change of pressure dealt with in figure 2 contributes to variation in central pressure considered in figure 1.

SPEED VS. DIRECTION OF MOVEMENT

Figure 4 is designed to reveal any correlation that may exist between the direction a cyclone takes and the speed

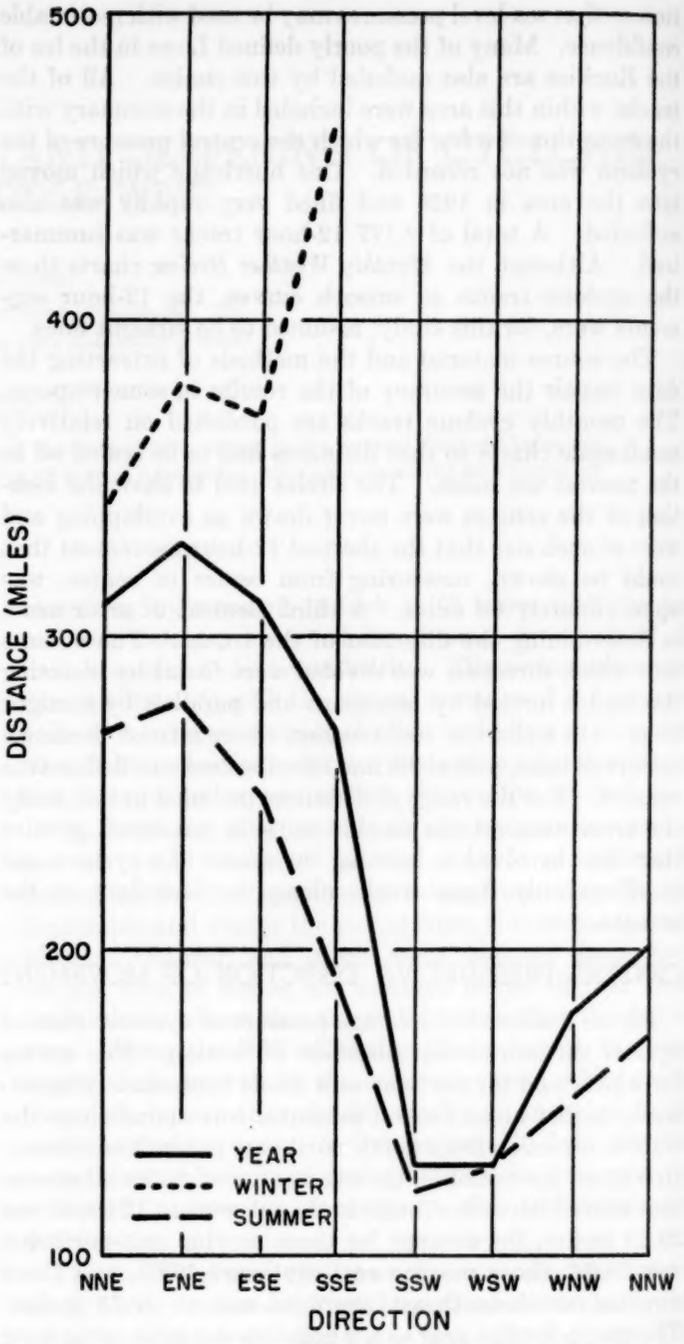

FIGURE 4.—Average distance traversed by cyclones in 12 hours plotted against direction of movement. The number of cases for each direction is the same as in figure 1.

with which it moves. Figure 5, which shows the percentage absolute mean deviation from the average distances plotted in figure 4, serves the usual purpose in providing a measure of the variability of the data from which the averages are derived. The minimum mean deviation in the first four octants, where the bulk of the data is concentrated, is for cyclones moving east-southeast in winter and amounts to plus or minus 123 miles from an average of 370 miles. Expressed in percentage the minimum absolute deviation for any of these four direction categories is 33 percent, the maximum 54 percent, and the

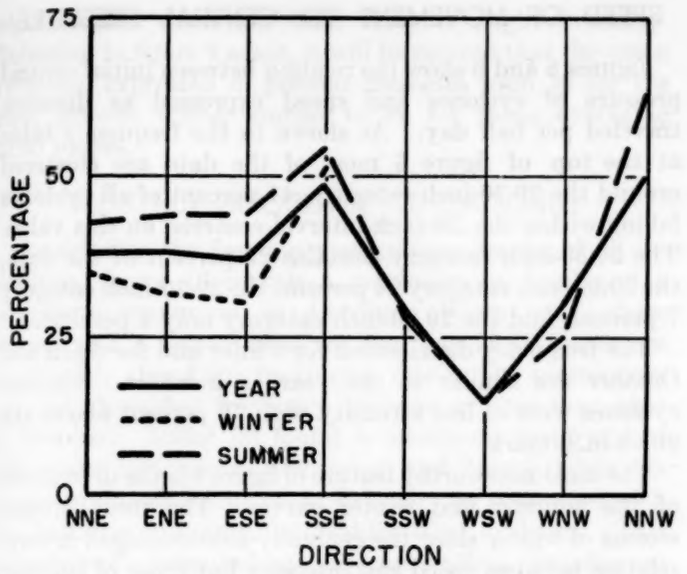

FIGURE 5.—Percentage absolute mean deviation of 12-hour distance traversed by cyclones plotted against direction of movement.

average near 40 percent. These deviations exceed most of the seasonal differences in speed of cyclones revealed in figure 4. Where such high absolute mean deviations are encountered, a relatively low order of verification must be expected of forecast rules relating speed and direction of motion of cyclones.

With these reservations in mind, figure 4 still has some points of interest. The maximum revealed by the curves for storms moving east-northeast is not of great magnitude but it is conspicuous for its persistence throughout the year. The distribution of data supports the assumption that this maximum is real and comprises, in effect, a path of least resistance for cyclones. Not only do storms move faster on this track, they are also more numerous. Forty-five percent of all Middle West cyclones in the decade of the 1920's moved east-northeast. The predominant direction of cyclones off the east coast of the United States is shown by Miller [3] to fall within this octant and Saucier [4] confirms this conclusion for Texas cyclones.

SPEED OF MOVEMENT VS. 12-HOUR PRESSURE CHANGE

Figures 6 and 7 deal with the influence of changing pressure on the speed of cyclone movement. Before discussing these graphs, it would be worth noting from the frequency table at the top of figure 6 that the cases fall into a remarkably symmetrical pattern, a distribution quite different from that of the preceding figures.

The relation between change in central pressure and distance travelled in 12 hours, illustrated in figure 6, has several points of interest. The curves for both summer and winter indicate that rapidly deepening storms move rapidly, with the greater speed associated with the larger pressure falls. The curve for all year, which includes April and October data in addition to those of summer and winter, emphasizes this conclusion. The storms of

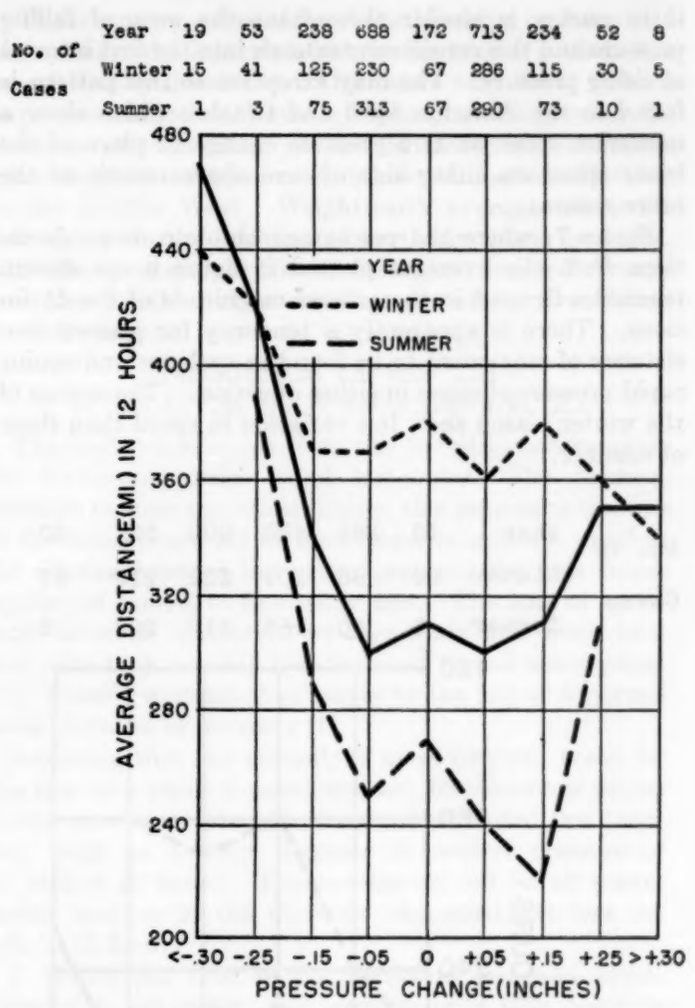

FIGURE 6.—Average 12-hour distance traversed by cyclones plotted against change in central pressure. Number of cases in each category is shown in table across top of graph.

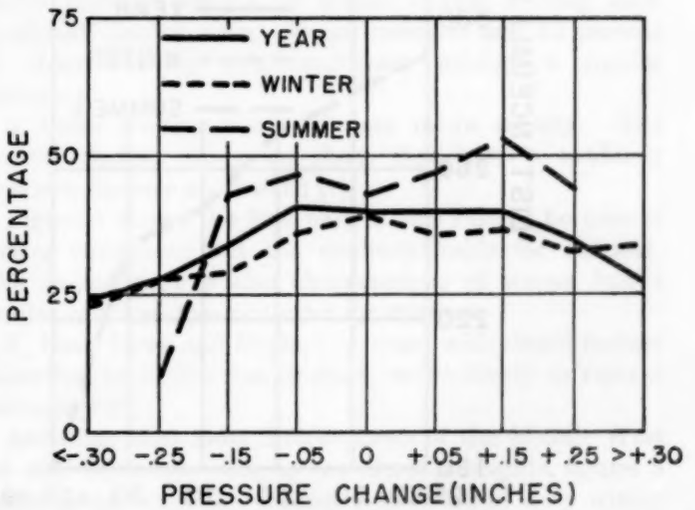

FIGURE 7.—Percentage absolute mean deviation of 12-hour distance traversed by cyclones plotted against change in central pressure.

rapidly increasing central pressure display such a considerable variation between winter and summer that no general conclusions appear justified. The pattern of all

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three curves is similar throughout the area of falling pressure and this consistency extends into the first interval of rising pressure. The only exception to this pattern is found in the data for April and October which show a minimum speed at zero pressure change in place of the lesser speed on either side of zero characteristic of the other seasons.

Figure 7, where the percentage absolute mean deviations from the averages plotted in figure 6 are shown, resembles figure 5 in the general magnitude of the deviations. There is apparently a tendency for greater consistency of movement to be found in cyclones undergoing rapid pressure changes in either direction. The storms of the winter season show less variation in speed than those of summer.

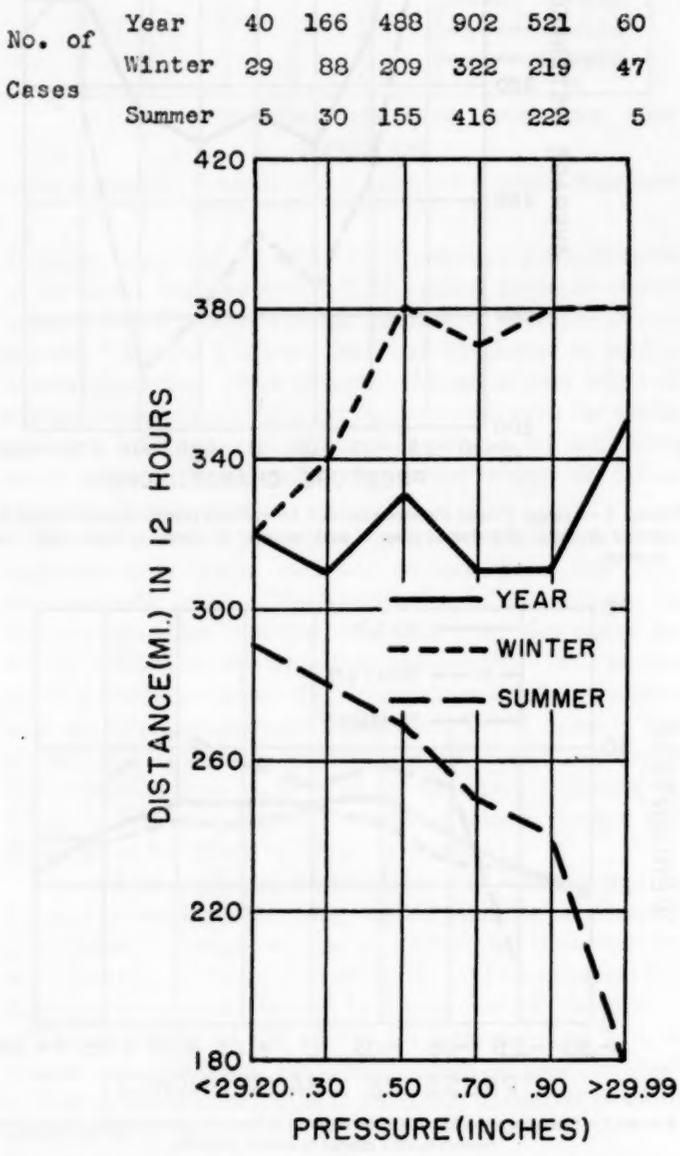

FIGURE 8.—Distance traversed in 12 hours plotted against initial central pressure of cyclones. Number of cases falling in each pressure interval is shown in table across top of graph.

SPEED OF MOVEMENT VS. CENTRAL PRESSURE

Figures 8 and 9 show the relation between initial central pressure of cyclones and speed expressed as distance traveled per half day. As shown in the frequency table at the top of figure 8 most of the data are clustered around the 29.70-inch category, 41 percent of all cyclones falling within the .20-inch interval centered on this value. The 29.50-inch category contains 23 percent of the data, the 29.90-inch category 24 percent, the 29.30-inch category 7 percent, and the 29.20-inch category only 2 percent.

The frequency distribution for winter and for April and October are similar to the year as a whole. Summer cyclones were of less intensity with 78 percent above the 29.60-inch mark.

The most noteworthy feature of figure 8 is the divergence of the summer and winter curves. The most intense storms of winter show the generally acknowledged inverse relation between speed and intensity but those of summer show an opposite tendency—the deeper storms moving more rapidly on the average throughout the range of intensity. The usefulness of the latter conclusion is qualified, however, by the much higher mean deviations characteristic of summer cyclones. As figure 9 indicates, the absolute mean deviation is 47 percent or greater for summer cyclones of central pressure greater than 29.60 inches and, as pointed out above, 78 percent of summer cyclones fall in this range.

Winter storms of all intensities move more consistently than those of summer, with the deeper Lows showing some-

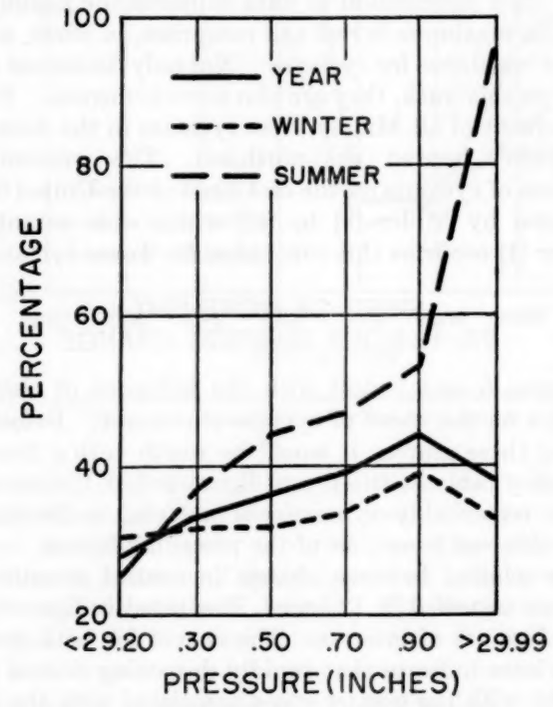

FIGURE 9.—Percentage absolute mean deviation of distance traversed in 12 hours plotted against initial central pressure of cyclones.

what smaller deviation than those of slight intensity. Referring to figure 9 again, it will be noticed that the mean deviation expressed in percent increases from 30 for the most intense winter storms to 39 for those averaging 29.90 inches.

MONTHLY FREQUENCY OF CYCLONES

Considering the frequency of cyclone tracks of all intensities, figure 10 reveals a maximum in April and a secondary maximum in October. When only those storms with a central pressure less than 29.60 inches are considered, the April maximum retains its prominence but the December frequency becomes greater than that of October. Miller [3] found a maximum frequency of east coast cyclones in December and March while his winter minimum occurred in February as compared with the January minimum for Middle West cyclones. This difference of minimum frequency must reflect the influence of the Atlantic coast, as a division of the Middle West cyclones into those south of latitude 40° N. and those north of it shows the January minimum common to both. Those cyclone tracks south of 40° N. display a much greater seasonal variation with the fall maximum in December in contrast to a well-defined October maximum for those tracks north of 40° N.

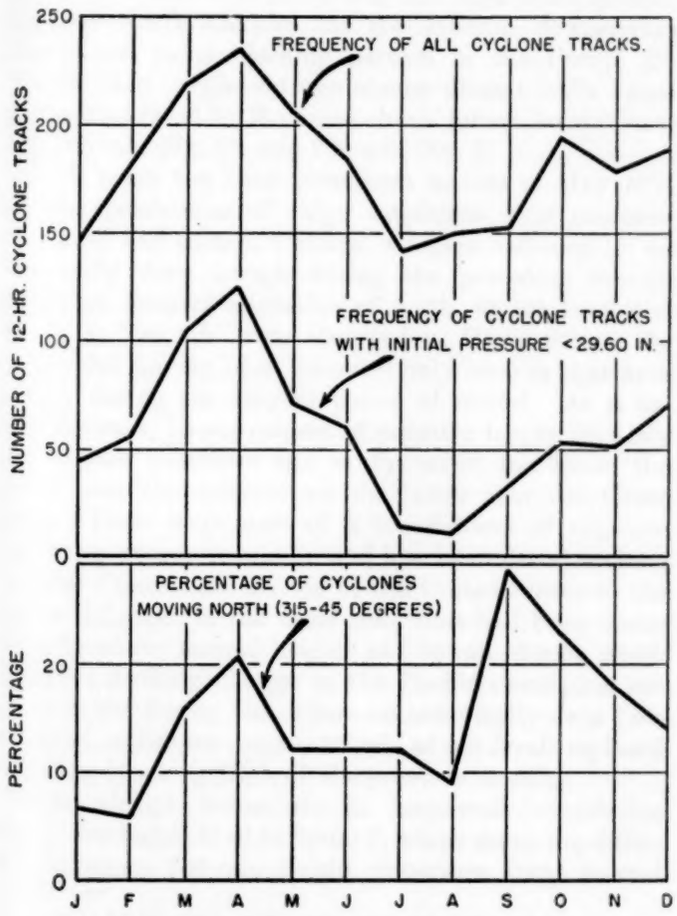

FIGURE 10.—Frequency of 12-hour cyclone tracks by months.

The frequency curve of northward moving cyclones also has spring and fall maxima but the September peak in this case is clearly dominant. This curve very likely reflects a preponderance of Texas cyclones, as Weightman [2] shows a corresponding northward deflection of Texas cyclones most conspicuous during September and October in the Middle West. Weightman's average tracks for late winter show a less marked northerly course for Lows, with the greatest northward deflection during February and March—the former month representing a minimum for this study.

DISCUSSION OF RESULTS IN RELATION TO FORECASTING RULES

The evidence adduced from this investigation bears on the forecasting rules listed hereunder. The premise, common to most statistical studies, that long-term changes in the atmosphere are of insufficient magnitude to affect the relation between the recent past and the near future applies, of course, to this study also. The lack of agreement between the results of this study and some forecast rules may possibly be attributed to this assumption.

1. Usually a storm that moves to the left of a normal track increases in intensity [1].

Assuming that the normal, or most frequent track for this area as a whole is east-northeast, 69 percent of winter storms moving to the left of normal exhibited this tendency with an average decrease in central pressure of .15 inch in 12 hours. The average net fall for all winter storms moving in the direction east-northeast was .08 inch in 12 hours.

2. *Storms that* start in the northwest and *move southeastward do not gather great intensity* until they begin to curve northward [1].

Referring to the italicized part of this rule, figure 3 shows that 56 percent of winter storms moving east-southeast display rising central pressure and 63 percent of those moving south-southeast exhibit a similar tendency.

3. Lows moving south of east move rapidly. The slowest moving Lows are those that have a tendency to move directly northward [1].

Figure 4 shows the first part of this rule to be true of winter conditions but the contrary holds for summer. The second part is also characteristic of winter but a similar relation does not exist for summer.

4. Deep Lows and Highs, i. e. those with closed isobars extending to 10,000 feet or more, move slowly or remain stationary [5].

Assuming that most intense Lows of the Middle West are cold Lows extending to considerable heights, figures 8 and 9 reveal that the difference in speed of deep winter Lows and those of slight or moderate intensity amounts to only 60 miles per half day while the absolute mean deviation of these same cyclones varies from 95 miles for those of less than 29.20 inches of central pressure to a maximum of 150 miles for those of less intensity. The

evidence indicates that this rule is of marginal utility in winter and could be reversed to good advantage in summer.

5. Cyclonic centers that are exposed to cyclogenesis, or deepening, are usually retarded, and cyclonic centers that are exposed to cyclolysis, or filling, are usually accelerated [5].

Figure 6 shows, for the decade of the 1920's, that rapidly deepening cyclones move with considerably greater speed than those associated with any other change in central pressure. Although the term "retarded" used in the first part of the rule is an acceleration term not directly comparable to the speeds treated in this study, it can still be inferred with considerable assurance that deepening cyclones are more likely to be accelerated than retarded. The behavior of filling cyclones is shown to be more erratic although some evidence of acceleration is apparent.

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THE WEATHER AND CIRCULATION OF MAY 1954[1]

A Circulation Reversal Effected by a Retrogressive Anticyclone During an Index Cycle

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THE CIRCULATION REVERSAL FROM APRIL TO MAY

It has been demonstrated by Namias [1] that monthly mean anomalies of temperature, precipitation, and height in the United States and adjacent areas persist less from April to May than for any other pair of months during the year except October-November. In fact, during the past decade these anomalies have shown more tendency for reversal than for persistence during the April-May period. This year the April-May reversal was even more marked than usual, not only for the United States but also for the circulation of most of the Northern Hemisphere. It will be recalled that April 1954 was characterized by a confluent jet stream and high index circulation over North America and the Atlantic, downstream from a low index blocking pattern in the Pacific [2]. This month's circulation was almost diametrically opposite, as illustrated by the mean charts for sea level (Chart XI), 700 mb. (fig. 1), and 200 mb. (fig. 2).

At all levels the most prominent feature of May 1954 was the persistence of ridge conditions over southern Greenland and eastern Canada, a region occupied by an abnormally deep trough during the preceding month. Maximum positive anomalies of 8 mb. at sea level and 380 ft. at 700 mb. were observed in Davis Strait, the latter value having been exceeded only once in that area in May during our 22-year period of record. As is usually the case, strong centers of negative height anomaly were located southeast and southwest of the block, the former near the Azores and the latter near the Great Lakes. These were part of a broad band of negative height departures at middle and low latitudes stretching from the Continental Divide of the United States to the eastern Atlantic, in the same zone that had been dominated by above normal heights at 700 mb. during April. The most striking change in the Pacific circulation occurred in the Bering Sea, where an abnormally deep Low (−340 ft. at 700 mb. and −12 mb. at sea level) replaced the strong blocking High of the previous month.

These abrupt transitions in large-scale circulation regimes are highlighted in figure 3, which maps the difference in mean 700-mb. height departure from normal between April and May of 1954. Inspection of the complete file (from 1933 to date) of charts showing this month-to-month anomalous height change reveals that this year's anomalous change of −680 ft. in the Bering Sea was the largest (regardless of sign) ever observed from April to May in any part of the Northern Hemisphere. The magnitude of this year's change in Davis Strait (+620 ft.) was exceeded in 1948 in the Pacific but never in the Atlantic or North America. Figure 3 also brings into sharp focus the blocking action which caused heights to rise more rapidly than normal from April to May throughout Canada while they actually fell (contrary to the normal trend) in most of the United States and adjacent oceans. In the mid-Pacific, on the other hand, the zonal westerlies increased markedly as large anomalous height falls in the north were compensated for by rises in the south. It is interesting to note that anomalous height changes in the western United States and eastern Pacific were relatively small, compared to those in other parts of the hemisphere, in agreement with the fact that April-to-May persistence during the past 20 years has been greater in this area than elsewhere [3].

The marked change in circulation pattern from April to May 1954 is also illustrated in striking fashion in figure 4A, giving the distribution of geostrophic wind speeds computed from figure 1. A single well-developed axis of maximum wind speed at 700 mb. (solid arrow) extended across middle latitudes during May from the Asiatic Coast into the Mediterranean, near 45° N. in the Pacific and 35° N. in the Atlantic. The corresponding position of this principal 700-mb. jet stream during April is delineated by the dashed arrow in figure 4A. Comparison of the solid and dashed arrows indicates that the westerly jet stream in the Pacific was 5° to 10° farther north in May than in April, but elsewhere it was displaced southward, by some 5° in the United States and as much as 20° in the eastern Atlantic. Wind speeds along the jet axis were also drastically altered during this April–May reversal, increasing from 25 to 45 m. p. h. in the Pacific but decreasing from 35 to 20 m. p. h. in the United States and the Atlantic. As a result this month's wind speeds were below normal throughout southern Canada and the northern Atlantic (fig. 4B), where they had been above

[1] See Charts I–XV following p. 140 for analyzed Climatological data for the month.

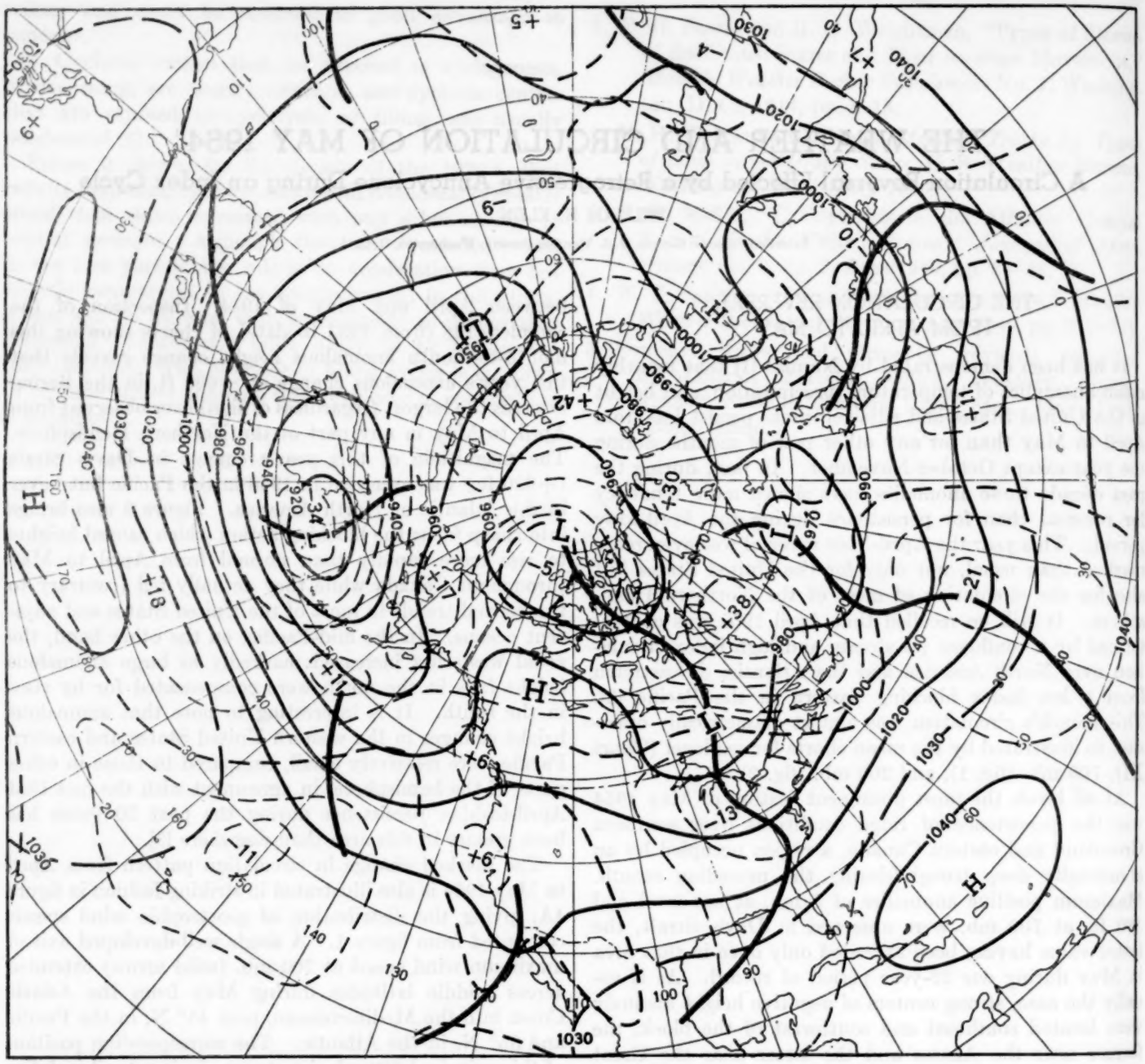

FIGURE 1.—Mean 700-mb. contours (solid) for May 1–30, 1954. Height departures from normal (dashed) are analyzed for every 50 ft. in North American area and for every 100 ft. elsewhere. Blocking and low index in North America and the Atlantic were accompanied by faster than normal westerlies in the mid-Pacific.

normal during April, and generally above normal in the western Pacific and southern Atlantic, where below normal speeds had prevailed the previous month.

Corresponding changes in wind speed distribution occurred at the 200-mb. level, where the principal features during May (fig. 2) as compared to those of April [2] included: (1) intensification and northward migration of the jet stream in the central Pacific; (2) weakening and southward shift of the polar front jet in North America, while the subtropical jet re-emerged in the south; (3) disappearance of the jet stream in the northern part of the Atlantic.

THE INDEX CYCLE

If attention is confined to the Western Hemisphere, then the abrupt transition of large-scale circulation pattern from April to May of 1954 may be interpreted as a manifestation of a general index cycle. This cycle has been defined by Rossby and Willett [4] as a basic but irregular fluctuation of the general circulation over a period of from 3 to 8 weeks from an essentially zonal pattern to one which is less zonal and more cellular in character; in short, a change from the high to the low index state. Although such index cycles may occur at

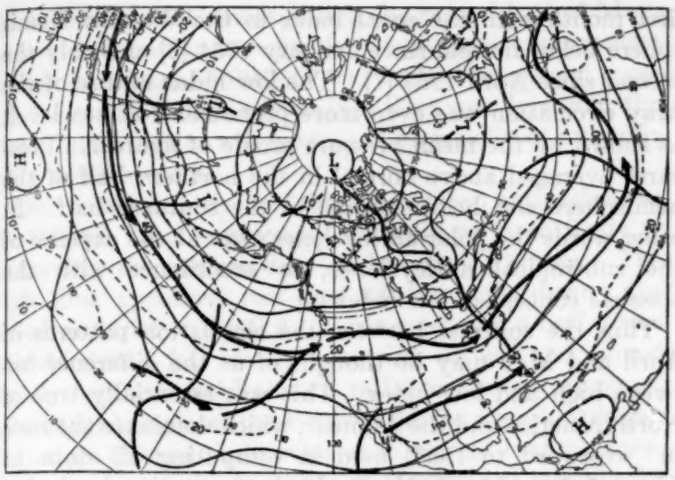

FIGURE 2.—Mean 200-mb. contours (in hundreds of feet) and isotachs (dashed, in meters per second) for May 1–30, 1954. Solid arrows indicate the average position of the 200-mb. jet stream which was stronger than, and north of, normal in the Pacific, but relatively weak and well to the south in eastern North America and the Atlantic.

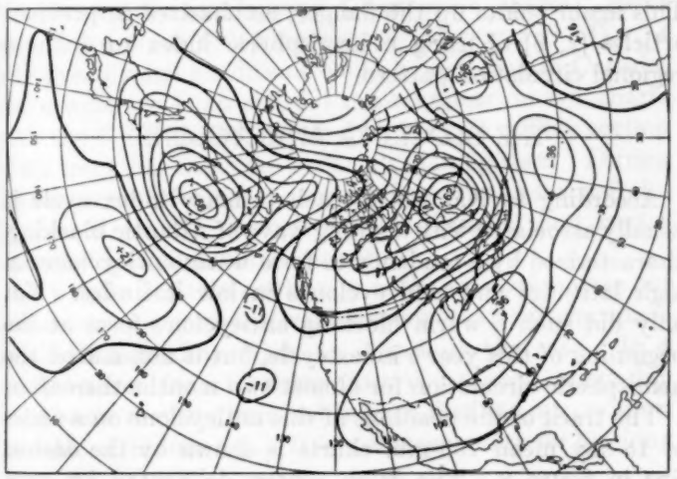

FIGURE 3. Change in mean 700-mb. height departure from normal from April to May 1954. The lines of equal anomalous height change are drawn at 50-ft. intervals with the center labeled in tens of feet. Changes in Bering Sea and Davis Strait were of record magnitude. Note weakening of westerlies at middle latitudes of North America and Atlantic due to blocking.

any time of the year, they are most frequent in late February or early March [5]. This year, however, no clear cut or prolonged index cycle was apparent during any of the winter months; apparently the primary cycle was not initiated until April.

The lower curve in figure 5 shows the time variation of 5-day mean values of the 700-mb. zonal (temperate) index computed twice-weekly from average heights at latitudes 35° N. and 55° N. in the Western Hemisphere. The curve starts with the index for the 5 days centered on March 15, the lowest value observed during 1954 up to that time. Prior to this date the 1954 graph showed a series of irregular short-period fluctuations, but thereafter a definite long-period index trend was clearly discernible. For the first 2½ weeks of this period the index increased steadily, reaching a high of 11.9 m. p. s. on April 2, the beginning of the index cycle proper. During the next 7 weeks the index

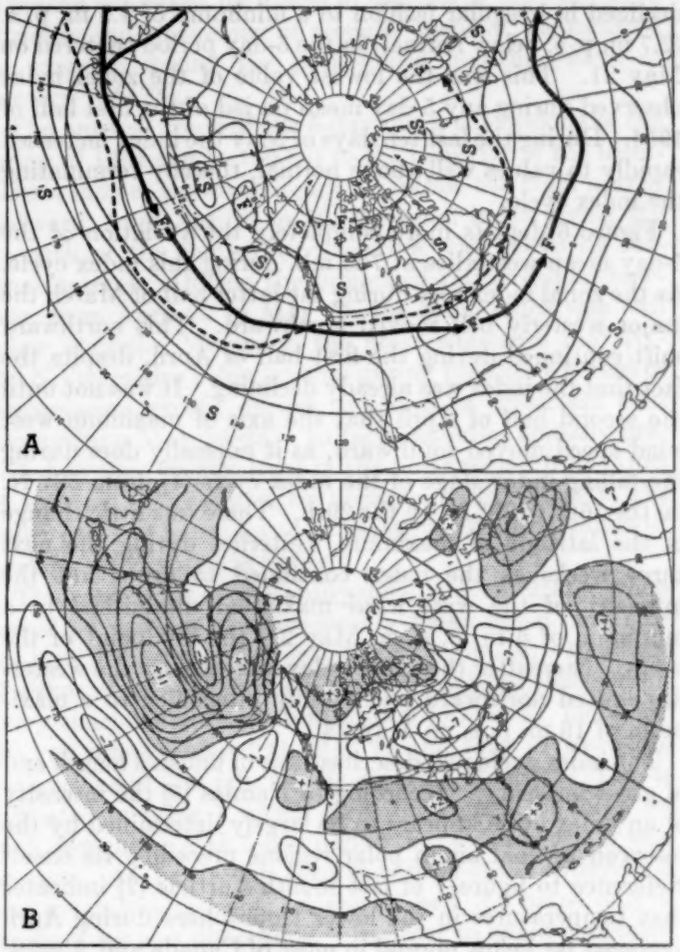

FIGURE 4.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for May 1–30, 1954. Solid arrows indicate average position of the 700-mb. jet stream during May, while dashed arrows show its position during April. The jet stream in the Pacific was 5° to 10° farther north in May than in April but elsewhere it was displaced southward.

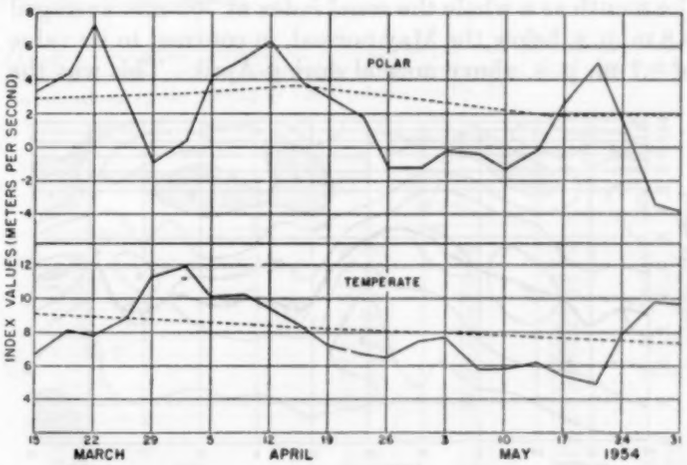

FIGURE 5.—Average strength of 700-mb. westerlies over the Western Hemisphere for polar (55° N.–70° N.) and temperate (35° N.–55° N.) regions. Solid lines connect 5-day mean index values (plotted at middle of 5-day period and computed twice-weekly), while dashed lines show variation of corresponding normal indices. Note long-period decline of the zonal (temperate) index from April 2 to May 21.

declined in irregular fashion to a minimum of 4.9 m. p. s. (2.7 m. p. s. below normal) in the 5-day period centered on May 21. This was the lowest value of the zonal index observed during any 5-day mean period of the first half of 1954. During the last ten days of May the index increased rapidly to values well above normal, thereby terminating the index cycle.

Figure 6 depicts more completely the variation of the 5-day mean westerlies at 700 mb. during this index cycle. As the zonal index rose during the latter half of March the major westerly belt moved northward. This northward shift continued during the first half of April, despite the fact that the index was already declining. It was not until the second half of April that the axis of maximum west wind speed moved southward, as it normally does during the falling index stage of the index cycle [4], from 52° N. on the 16th to 38° N. on the 29th. There was little change in the latitude of maximum westerlies during the next three weeks as the index continued to drop; but the intensity of the west wind maximum diminished to a minimum of 6 m. p. s. on May 21, the low point of the cycle. Thereafter the zonal index increased as the westerlies shifted northward and rapidly intensified to a maximum of 16 m. p. s. on May 28.

The index cycle just described was of unusual length and of great intensity. According to Namias [5] the intensity of an index cycle appears to be largely determined by the reservoir of cold air in polar regions preceding its onset. Reference to figure 1 of last month's article [2] indicates that temperatures in the lower troposphere during April averaged far below normal in most of Canada and Alaska. This cold air was contained in the north by fast westerlies during April; but it came south in great force when the westerlies weakened in May, thereby contributing to the strength of this year's index cycle.

Figure 5 shows that the 5-day mean zonal index was below normal during all but the last week of May. For the month as a whole the zonal index at 700-mb. averaged 0.8 m. p. s. below the May normal, in contrast to its value of 0.7 m. p. s. above normal during April. This was the first month with the zonal index in the Western Hemisphere below normal since January 1954 [6] and only the second since April 1953 [7]. The low index nature of the May circulation was even more pronounced at sea level, as shown by the mean pressure profile of figure 7. Pressures averaged above normal in the northern half of the hemisphere and below normal in the southern half. In other words the polar anticyclones grew at the expense of the subtropical anticyclones, in accordance with the classical concept of low index [4].

Thus the contrast between the circulation patterns of April and May may be thought of as the difference between high and low index. This was essentially true of North America and the Atlantic, which dominate the zone (0° westward to 180°) used in computing all data in figures 5, 6, and 7. In the Pacific however, the circulation change from April to May was opposite in character. Here low index conditions during April were replaced by a high index circulation in May, as indicated in figures 1 to 4. This again points up the danger, emphasized in previous articles [2, 6] of using a hemispheric index to define a regional circulation pattern.

THE BLOCKING ANTICYCLONE

According to Namias [5] each primary index cycle is usually associated with a strong wave of Atlantic blocking, characterized by a tendency to form warm anticyclones in high latitudes and cold cyclones in low latitudes. Not only did such a warm blocking anticyclone form at the beginning of this year's index cycle, but it dominated the hemispheric circulation for almost two months thereafter.

The track of the positions of this anticyclone on a series of 15-day mean 700-mb. charts is shown by the dashed line in figure 8. The High center, delineated by open circles, was over the British Isles during the second half of April, near northern Labrador during the first half of May,

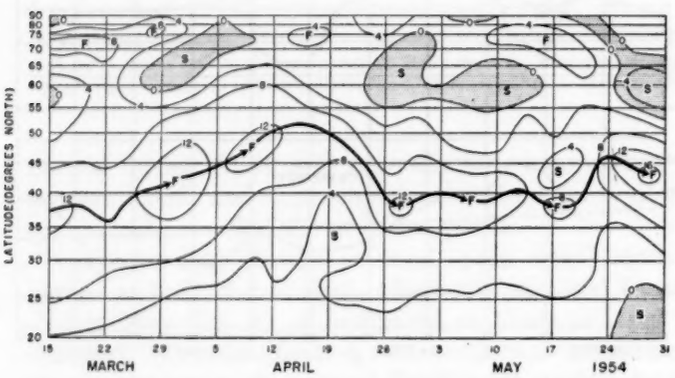

FIGURE 6.—Time-latitude section of 5-day mean zonal wind speed in the Western Hemisphere in meters per second at 700-mb., corresponding to period shown in figure 5. The latitude of the axis of maximum west wind speed (heavy arrows) increased from mid-March to mid-May but then decreased to low values during May. Note easterlies (shaded) in polar regions.

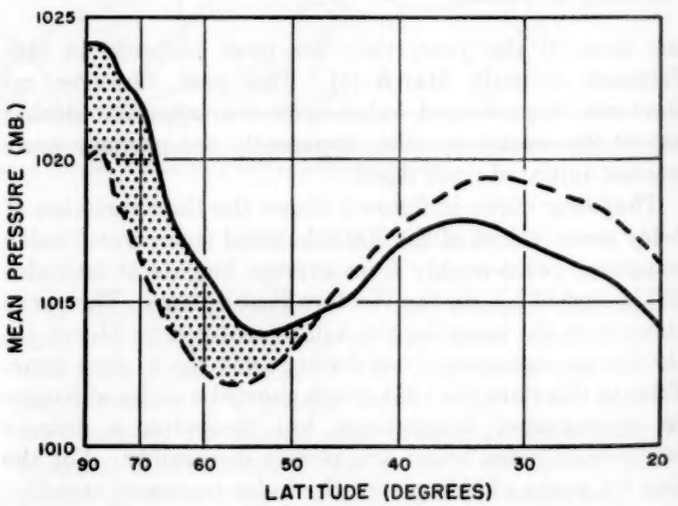

FIGURE 7.—Mean sea level pressure profile in the Western Hemisphere for May 1-30, 1954 with normal May profile dashed. Note positive anomaly of pressure north of 48° N. (shaded area) and negative anomaly to the south.

and over western Canada during the second half of May. A somewhat similar retrogressive 15-day mean anticyclone during the winter of 1949–50 was formed by several separate 5-day mean High centers [8]. This year, however, the 15-day mean center was composed essentially of only one 5-day mean system.

The remarkable track of this 5-day mean anticyclone at the 700-mb. level is given by the solid curve in figure 8, connecting the centers denoted by crossed circles. The High first appeared just east of Bermuda during the period centered on April 9. For a week and a half it was embedded in a fast westerly steering current and moved rapidly northeastward along a rather common trajectory. After stagnating near the British Isles for a week, it began to recurve toward the northwest in a great cyclonic loop. Upon reaching latitude 60° N. it retrograded steadily for almost two weeks across the Denmark and Davis Straits into Hudson Bay. Up to this point its continuity, although unusual, could clearly be followed on our series of twice-weekly overlapping 5-day mean charts. However, for a week following the period centered May 14 only broad ridge conditions could be detected in Canada, and a separate High cell did not reappear on our charts until the 5-day period centered on May 24. This portion of the track has therefore been dotted in figure 8. During the last week of May the anticyclone was again well defined as it moved through western Canada, first northwestward and then northeastward.

On a daily basis the continuity of the anticyclone was not so clear since several eastward-moving daily systems made up the retrograding High, as is usually the case. It is rare, however, for a blocking anticyclone, even on a 5-day mean basis, to retrograde bodily from England into western Canada, as this one did. It is more customary for blocking to spread westward by means of successive intensification of ridges and weakening of troughs upsteam, as occurred for example during the pronounced blocking wave of January 1954 [6].

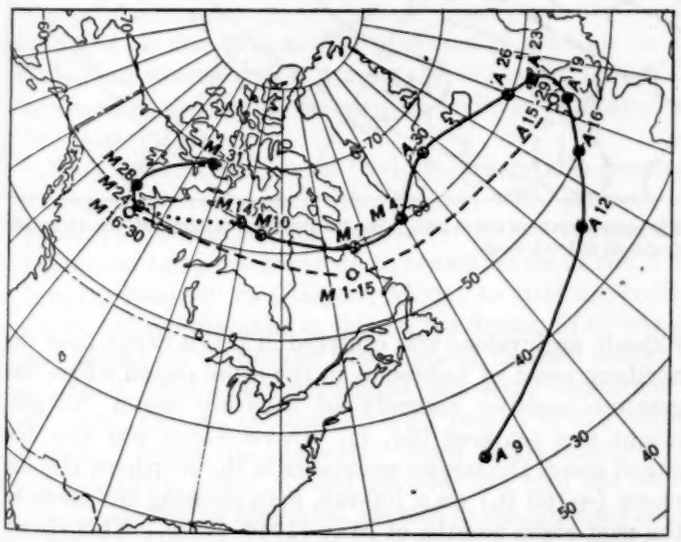

FIGURE 8.—Trajectory of the 700-mb. anticyclone of the spring of 1954, as determined from a series of 15-day mean charts (dashed track) and 5-day mean charts (solid track except dotted in region of uncertain continuity). Open circles locate the center of the 15-day mean anticyclone starting with the period April 15–29 and ending with the period May 16–30. Crossed circles indicate the center on successive 5-day mean maps (computed twice-weekly) from the period centered April 9 (A 9) to the period centered May 31 (M 31).

The unusual track of the 5-day mean anticyclone of the spring of 1954 can be related to the behavior of the hemispheric indices shown in figure 5. While the High moved eastward, from April 9 to 16, the zonal index giving the strength of the temperate westerlies was above its seasonal normal. During the prolonged retrogression, however, from April 20 to May 24, the zonal index was well below normal. Moreover, the polar westerlies (55° N.–70° N.) were also below normal during the entire period of retrogression except during the week of uncertain continuity from May 16–23. In fact, easterlies actually prevailed at the 700-mb. level in the polar region from April 25 to May 14, as shown by negative index values in the upper curve of figure 5 and by negative (shaded) values of westerly wind speed in figure 6.

The continuity of the anticyclone is even clearer when traced on a series of twice-weekly 5-day mean charts of sea-level pressure or 700-mb. height anomaly. In terms of either of these elements the center could be followed on every chart of the series from April 9 to May 31, including the two maps centered on May 17 and May 21 when the anticyclone at 700 mb. lost its separate identity. This is indicated in table 1 which gives the central intensity of each element on each 5-day period that a closed center was present. At the 200-mb. level the center of the anticyclone was much less distinct; on almost half the maps only a strong ridge was discernible. In order to avoid confusion the tracks of the centers of sea-level pressure, 700-mb. height anomaly, and 200-mb. height have not been included in figure 8. They generally coincided quite closely with the track of the anticyclone at 700 mb. with the centers of the first two elements slightly to the north and of the last slightly to the south of the corresponding 700-mb. High center.

TABLE 1.—*Central intensity of 700-mb. height and its anomaly, sea-level pressure, and 200-mb. height along the track of the 5-day mean anticyclone of the spring of 1954 (shown in fig. 8)*

5-day mean period	700-mb. height (ft.)	700-mb. height anomaly (ft. above normal)	Sea-level pressure (mb.)	200-mb. height (ft.)
April 7–11	10, 500	490	1033	----------
10–14	10, 420	550	1035	39, 100
14–18	10, 480	750	1038	39, 200
17–21	10, 160	500	1030	39, 300
21–25	10, 050	420	1028	38, 300
24–28	10, 060	500	1031	----------
April 28–May 2	10, 090	680	1036	38, 500
May 1–5	10, 110	750	1033	----------
5–9	10, 170	860	1036	39, 600
8–12	10, 100	640	1032	----------
12–16	9, 830	360	1025	----------
15–19	----------	270	1021	----------
19–23	----------	240	1023	----------
22–26	9, 950	110	1025	38, 700
26–30	10, 000	320	1027	38, 800
May 29–June 2	10, 090	570	1030	39, 000

Table 1 shows that the 700-mb. height at the center of the anticyclone fell almost 500 ft. during April as it moved

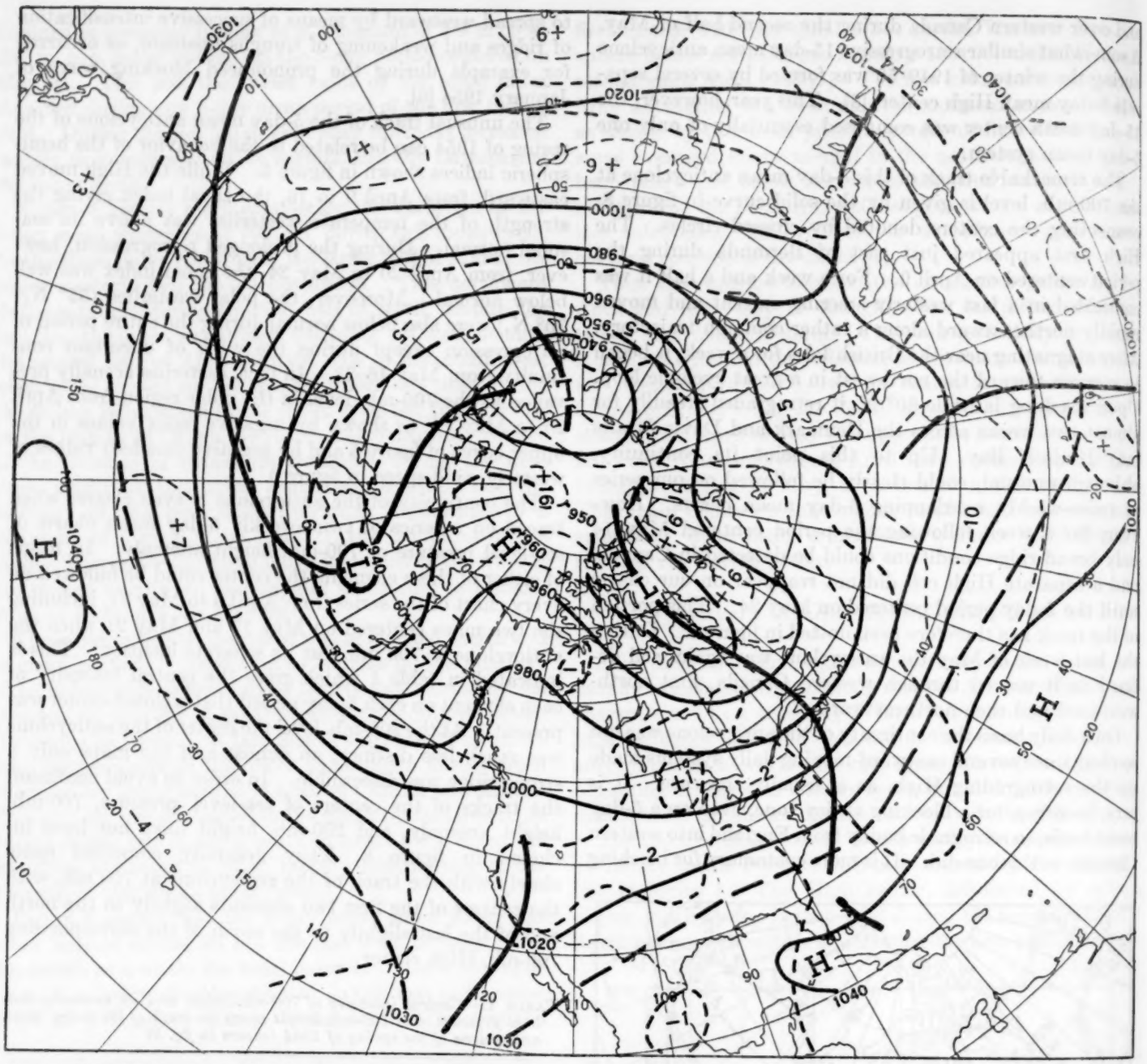

FIGURE 9.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for eight Mays from 1946 to 1953. Note the similarity to May 1954 (fig. 1), particularly the strong positive anomaly (block) in Davis Strait.

northward from a warmer to a colder region. On the other hand, pressure at the center of the sea level anticyclone remained rather constant (between 1028 and 1038 mb.) for over a month after its genesis. In mid-May the central intensity of all elements decreased as the High center vanished aloft, only to increase again at the end of the month. Maximum values of 700-mb. height anomaly and 200-mb. height during the entire period of study and maximum values of 700-mb. height and sea level pressure during the month of May were all observed during the 5-day period from May 5 to 9. At this time the 700-mb. anticyclone was centered in Davis Strait near the northern coast of Labrador, in the same region where the greatest positive anomaly of monthly mean 700-mb. height was centered (fig. 1). Davis Strait was also the site of one of the largest anomalies in the Northern Hemisphere (+160 ft.) on a 700-mb. map showing the mean of the past eight months of May (1946–1953). This chart, reproduced in figure 9, bears a striking resemblance to the corresponding chart for this May, figure 1, in other parts of the hemisphere as well. This implies either a systematic error in our long-period normals or a recent climatic

fluctuation of the general circulation. It is also noteworthy that Atlantic blocking activity for the periods 1933–1940 and 1945–1949 was more frequent during May than during any other month of the year [9].

THE WEATHER

The reversal in circulation from April to May produced a marked change in temperature regime in the eastern two-thirds of the United States. Whereas monthly mean temperatures had been much above normal in this area in April [2], they averaged from 2° to 7° F. below normal during May (Chart I-B). Greatest negative departures were observed in the Upper Mississippi Valley and in the Southeast. The first decade of May was one of the coldest on record in Minnesota, where a heavy snowcover ranging up to 15 inches was reported around Lake Superior on the 10th. Minimum temperatures on May 1 and 2 in Montana and during the next few days at many stations in the Mississippi Valley were the coldest ever recorded for May. In the Southeast record low temperatures for so late in the season were reported on May 22 at Jacksonville, Fla. (51°), Birmingham, Ala. (41°), and Augusta, Ga. (42°).

This cold weather can be readily associated with the monthly mean 700-mb. chart (fig. 1), which shows that the eastern two-thirds of the United States was dominated by stronger than normal northerly wind components, below normal heights, and cyclonic curvature at the 700-mb. level. At sea level (Chart XI) the nose of high pressure projecting southeastward from central Canada through the upper Mississippi Valley into the Southeast well delineates the axis of coldest air at the surface. Much of this cold air was carried into the country from the frozen Hudson Bay region by northeasterly winds, relative to normal, at sea level (Chart XI inset). The severity of the cold outbreaks in the United States can also be attributed to the presence of abnormally cold air in the Canadian source region during the preceding month [2], a situation similar to that which occurred in November 1951 [10, 11].

West of the Continental Divide temperatures generally averaged above normal during May, with greatest departure (6° F.) in central Nevada. On the 19th and 20th maximum temperatures rose to record levels in the West, ranging from 93° in Glasgow, Mont., to 104° in Needles, Calif. Warm weather in this region during May was accompanied by a stronger than normal thermal trough at sea level, above normal heights and weak westerlies at 700 mb., and an abnormally deep trough in the eastern Pacific. Along the immediate coast temperatures averaged slightly below normal because the cool sea breeze was intensified by abnormal warmth in the interior valleys.

The predominance of blocking activity in Canada and a strong cyclonic circulation to its south were responsible for a good deal of storminess (Chart X) and precipitation (Chart III) in the eastern two-thirds of the United States. Above normal rainfall amounts were recorded all along the

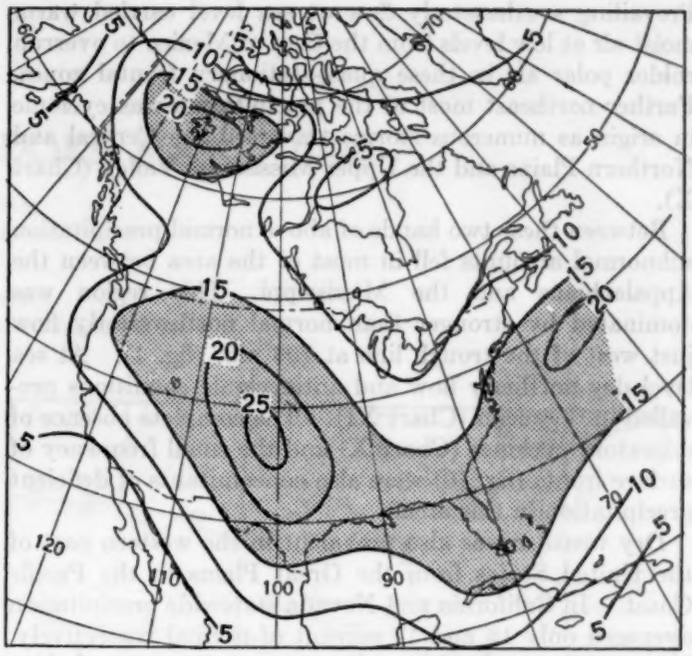

FIGURE 10.—Number of days in May 1954 with surface fronts of any type (within squares with sides approximately 430 nautical miles). Frontal positions taken from *Daily Weather Map*, 1:30 p. m. EST. Note great frequency of fronts in Texas Panhandle.

Atlantic Coast (with a few exceptions) in southerly flow ahead of the 700-mb. trough and its related abnormally deep mean trough at sea level. An unusually large number of daily cyclones moved up along the coast, and some recurved into New England or the Maritime Provinces because of the block. On May 16 one of these storms, produced 5.74 inches of rain in 24 hours at Boston, Mass., a new 24-hour record. Total rainfall during May at Boston was 13.38 inches, almost 5 times the normal amount and 1 inch more than the total recorded in any month of the year in a long period of record dating back to 1818. Heavy precipitation throughout New England was favored by strong southeasterly wind components, relative to normal, on the monthly mean charts for both sea level and 700 mb.

A larger area of above normal precipitation during May extended from southern New Mexico northeastward to Misssouri and thence northward to the Canadian border. This area included west Texas and Oklahoma, where a prolonged drought had been broken during April [2]. The additional rains during May resulted in reports at the month's end of the best moisture situation in many years. Also included in the wet area were central and southern Iowa where many small streams were overflowing at the close of the month. Floods were also reported in parts of New Mexico on the 18th when 3 to 4 inches of rain fell overnight.

Heavy precipitation in Texas and neighboring States was related to an unusual concentration of surface fronts in this area. Figure 10 shows that fronts were located in the Texas Panhandle on as many as 25 days of the month.

Prevailing southeasterly flow at sea level carried warm moist air at low levels from the Gulf of Mexico to overrun colder polar air in these quasi-stationary frontal zones. Farther northeast most of the precipitation was cyclonic in origin as numerous storms traversed the Central and Northern Plains and the Upper Mississippi Valley (Chart X).

Between these two bands of above normal precipitation subnormal amounts fell in most of the area between the Appalachians and the Mississippi. This region was dominated by stronger than normal northwesterly flow just west of the trough line at 700 mb. (fig. 1). At sea level dry northerly flow and anticyclonic conditions prevailed in the mean (Chart XI). The complete absence of migratory cyclones (Chart X) and the small frequency of surface fronts (fig. 10) were also concomitants of deficient precipitation in this area.

Dry weather was also prevalent in the western part of the United States from the Great Plains to the Pacific Coast. In California and Nevada statewide precipitation averaged only 16 and 17 percent of normal respectively. This region was dominated by stronger than normal ridge conditions at the 700-mb. level and by a thermal trough at sea level. The normal influx of moisture from the Pacific was greatly weakened by the prevalence of easterly wind components, relative to normal, at both sea level and 700 mb. in most of the eastern Pacific and western North America. As a result only one migratory cyclone entered North America from the Pacific all month long (Chart X).

An interesting sidelight of this year's weather has been the pronounced 2-month cycle of monthly mean temperature in the eastern two-thirds of the United States. Surface temperatures in most of this area averaged near to below normal during January 1954, above and much above during February, near to below normal during March, above to much above during April, below and much below during May, and near to much above during June. Relatively cool weather during the months of January, March, and May was associated with recurrent blocking activity, while warm weather during the other months of the first half of the year was accompanied by fast westerly flow along the United States-Canadian border. No explanation for these large-scale oscillations or indications of their future duration is available at present.

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OKLAHOMA TORNADOES, MAY 1, 1954

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INTRODUCTION

During the afternoon and early evening of May 1, 1954, thirteen confirmed tornadoes raked across Oklahoma. Official severe storm data lists two persons killed as a direct result of tornadoes and two more by drowning in floodwaters. Ninety-one people were injured. Destruction and damage to property and crops mounted to an estimated $3,353,000. This figure includes damage by numerous hail and windstorms; hail stones ranged up to "golf ball" size and winds up to 90 miles per hour. A few tornadoes occurred in northern Texas and southern Kansas, but are not included in this report because of the absence of final data at the time of writing. The location of tornadoes in Oklahoma is shown in figure 1.

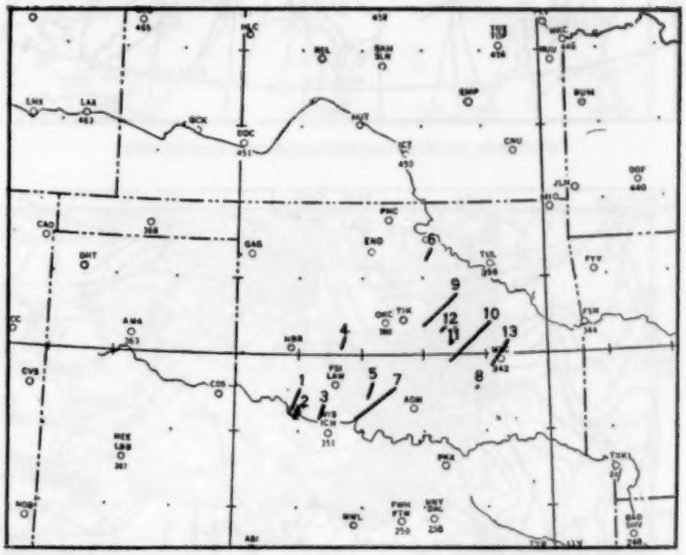

FIGURE 1.—Oklahoma tornadoes on May 1, 1954 (May 1-2 GMT): 1. 2010-2230, 2. 2130, 3. 2200, 4. 2250-2255, 5. 2330-0530, 6. 2342-2358, 7. 2345-0030, 8. 0000, 9. 0000-0120, 10. 0000-0210, 11. 0015, 12. 0105-0110, 13. 0120-0220.

GENERAL LARGE SCALE FEATURES

Some of the more important synoptic features that preceded the tornadoes are as follows: A surface frontal wave was near the northern Minnesota border early on the 29th of April. Following northeastward movement of this wave, very cold air advanced southward over the Central Plains. During the 30th, another wave advanced eastward across the Plains permitting the second surge of cold air to penetrate southward as far as northern Texas (fig. 2). Both of these waves were accompanied by tornado outbreaks throughout the Midwest. Some 48 hours prior to the occurrence of the tornadoes of May 1, there was a very sharp northwesterly jet at 500-mb. over California with the maximum wind speed over the northern portion of the State. This was still evident during the morning of the 30th (fig. 5). Associated with this jet and the northwest–southeast tilt of the 500-mb. trough was surface cyclogenesis over Nevada (fig. 2). The importance of this tilt and wind structure for development of storminess over the lower and mid-latitudes was pointed out by the Olivers [1].

The surface Low formed by this cyclogenesis was rather complex. It progressed eastward across the southern Rockies during the night of the 30th and the morning of the 1st (fig. 3). Meanwhile, the jet stream was being translated eastward from California into Nevada and the maximum winds were being observed in the trough (fig. 6). During the late morning of the 1st, the surface Low was becoming well organized over eastern New Mexico. This organization, along with the isallobars and the upper air pattern indicated rapid east-northeast movement. Other features of interest were the nearly steady pressures along the east coast and the slow anticyclogenesis just to the northwest of the Dakotas. Figures 4 and 7 show the surface and 500-mb. charts near the conclusion of the tornado activity. The surface Low had moved into south-central Oklahoma and the strong winds on the 500-mb. chart had moved through the trough.

SMALLER SCALE FEATURES

Surface sectional charts have been prepared for 3-hourly intervals on the 1st until near the time of the first tornado occurrence and for one-hourly intervals during the time of most of the tornado activity. Isobars on the charts of figures 8 through 16 were originally drawn for 1-mb. intervals but only every third isobar is reproduced here for clarity. Vertical cross sections (not reproduced) were drawn to support the frontal analyses. Important features to be noted are the advance of the warm front over southeastern Oklahoma and acceleration of the cold front

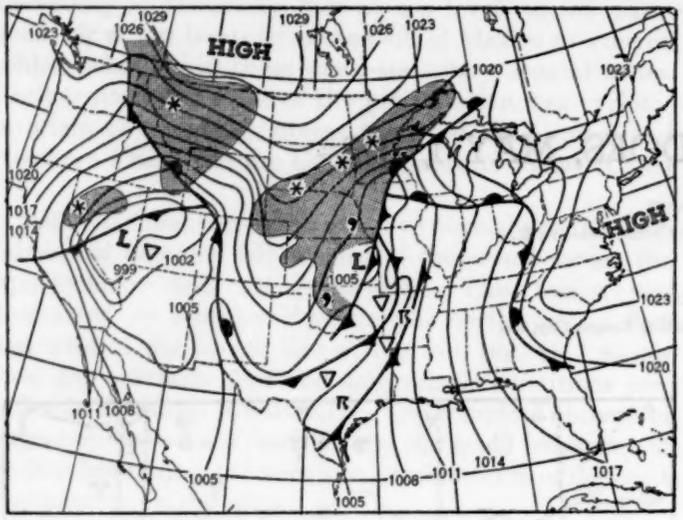

FIGURE 2.—U. S. surface chart, 1530 GMT, April 30, 1954.

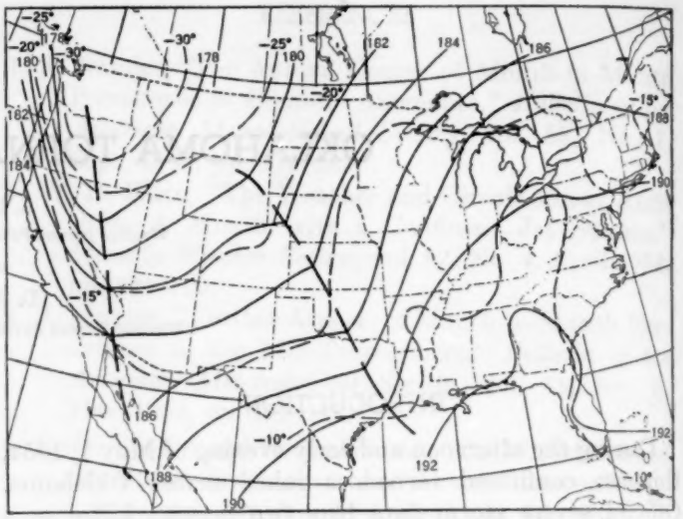

FIGURE 5.—U. S. 500-mb. chart, 1500 GMT, April 30, 1954.

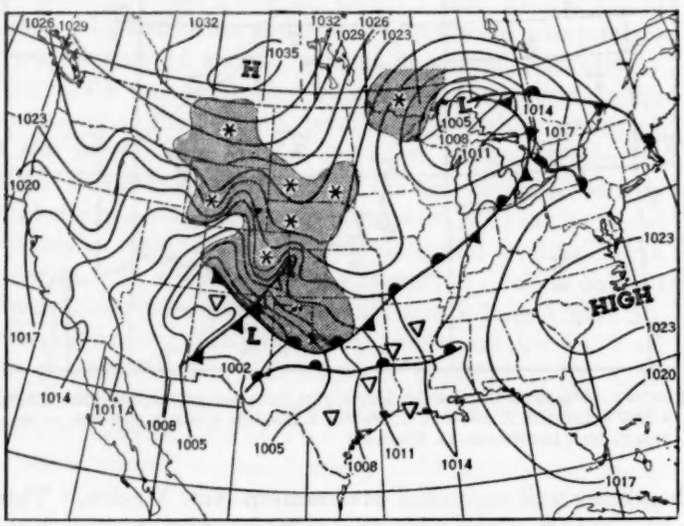

FIGURE 3.—U. S. surface chart, 1530 GMT, May 1, 1954.

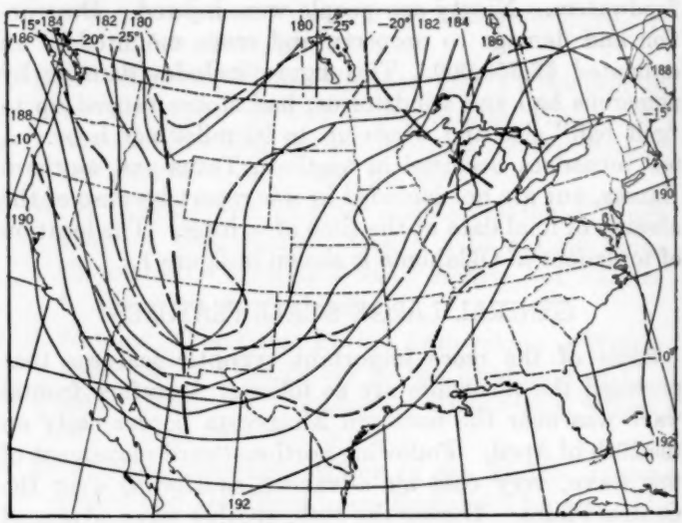

FIGURE 6.—U. S. 500-mb. chart, 1500 GMT, May 1, 1954.

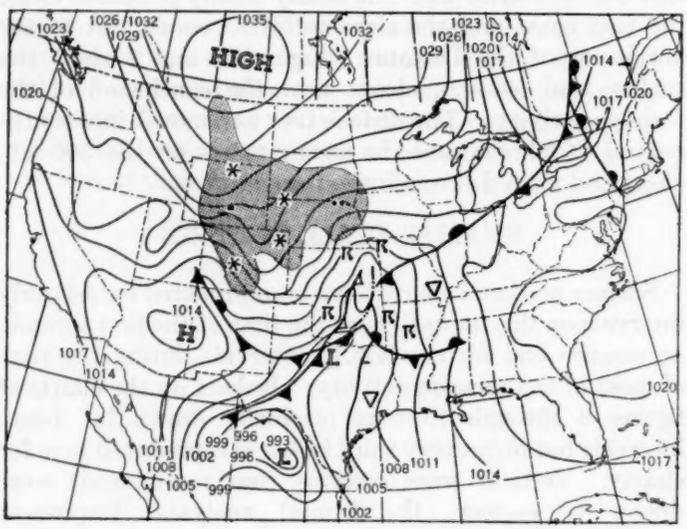

FIGURE 4.—U. S. surface chart, 0330 GMT, May 2, 1954.

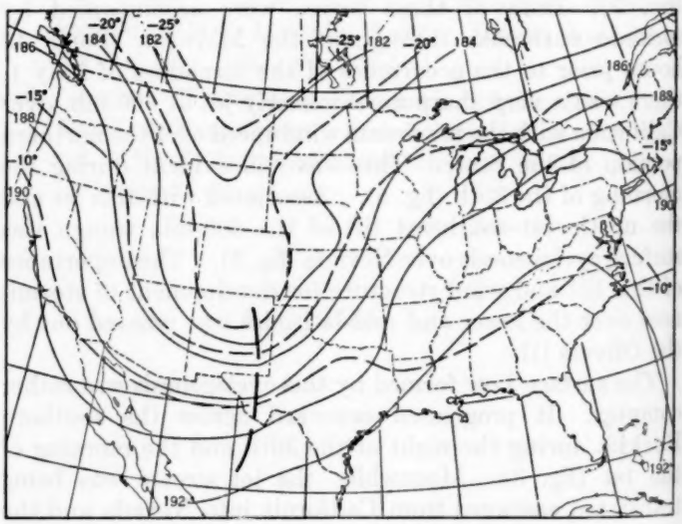

FIGURE 7.—U. S. 500-mb. chart, 0300 GMT, May 2, 1954.

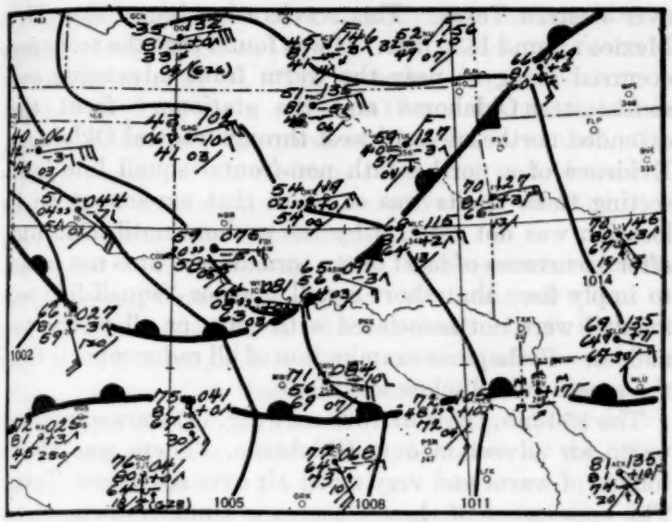

FIGURE 8.—Surface chart, 1530 GMT, May 1, 1954.

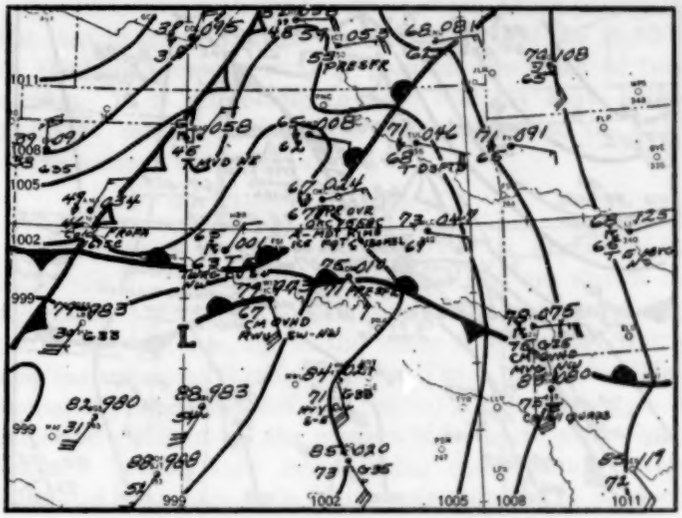

FIGURE 11.—Surface chart, 2230 GMT, May 1, 1954.

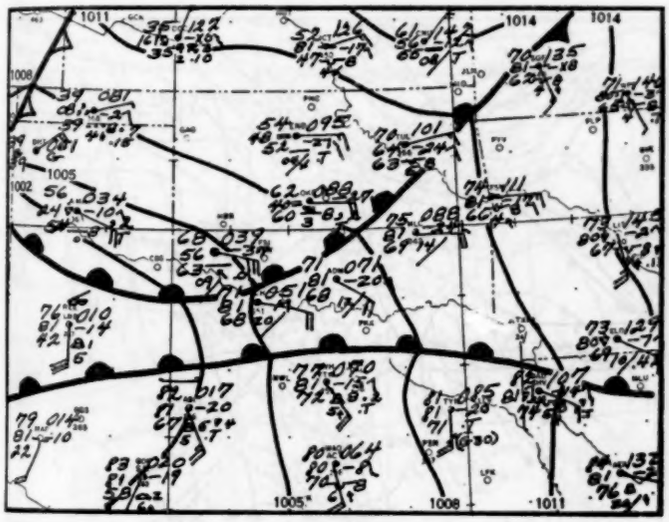

FIGURE 9.—Surface chart, 1830 GMT, May 1, 1954.

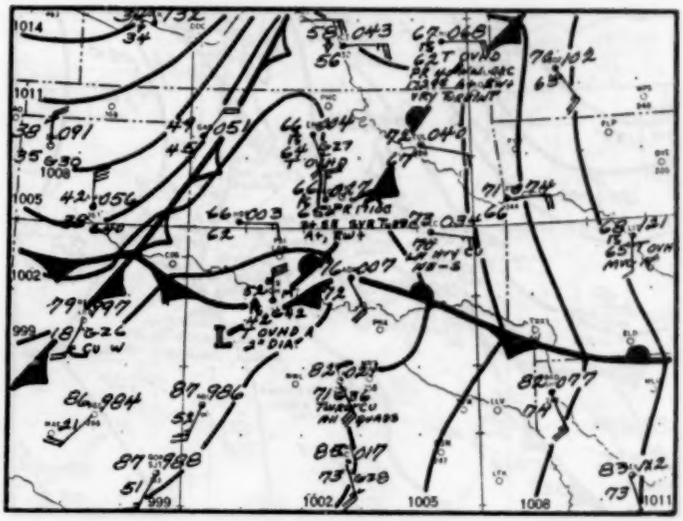

FIGURE 12.—Surface chart, 2330 GMT, May 1, 1954.

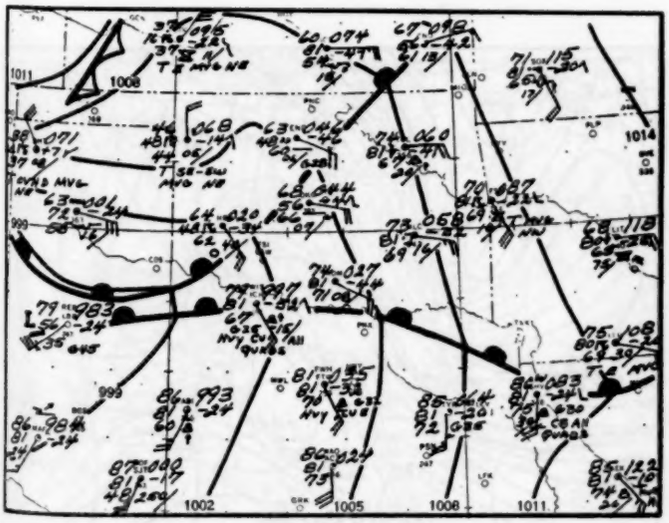

FIGURE 10.—Surface chart, 2130 GMT, May 1, 1954.

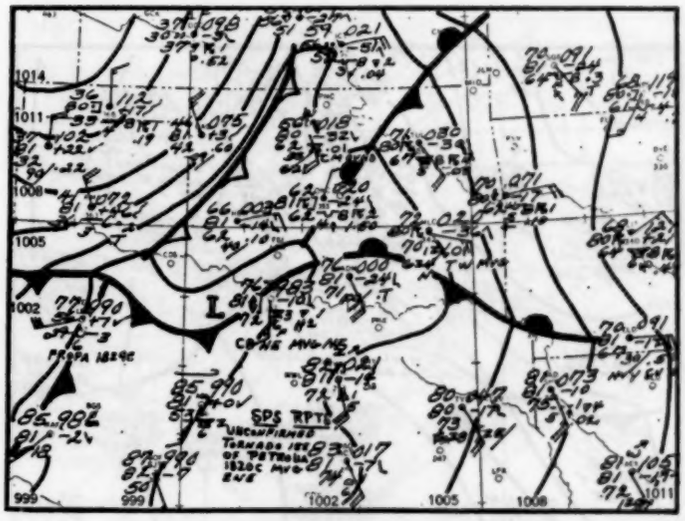

FIGURE 13.—Surface chart, 0030 GMT, May 2, 1954.

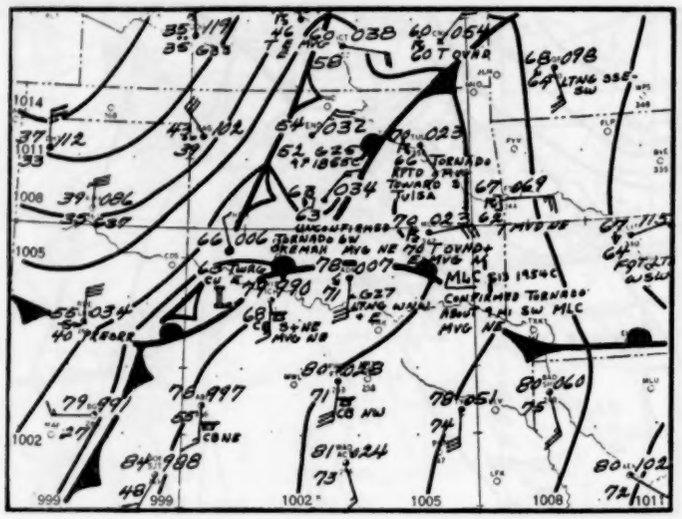

FIGURE 14.—Surface chart, 0130 GMT, May 2, 1954.

over western Texas. This acceleration began over New Mexico around 1830 GMT. It was found that the tornadoes occurred along or near the warm front advancing over southeastern Oklahoma and the stationary front that extended northeast–southwest through central Oklahoma. Evidence of a north–south non-frontal squall line intersecting these fronts was so weak that agreement on its location was not reached by the authors until 0230 GMT, after occurrence of most of the tornadoes. It is not meant to imply here that short squall lines or "squall-line segments" were not associated with some or all of the tornadoes. Perhaps an examination of all radar reports from the area would disclose such lines.

The 850-mb. chart at 1500 GMT (fig. 17) showed marked warm air advection over Oklahoma. There was also a tongue of warm and very moist air over southwest Texas. The importance of these features in thunderstorm, instability line, and tornado forecasting has been discussed in

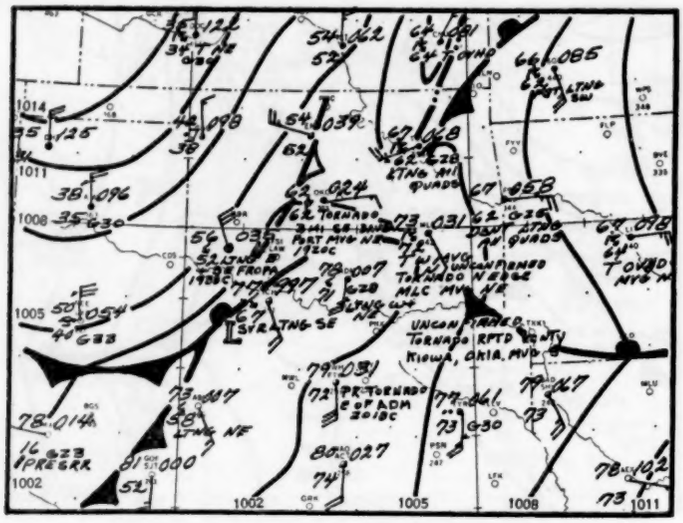

FIGURE 15.—Surface chart, 0230 GMT, May 2, 1954.

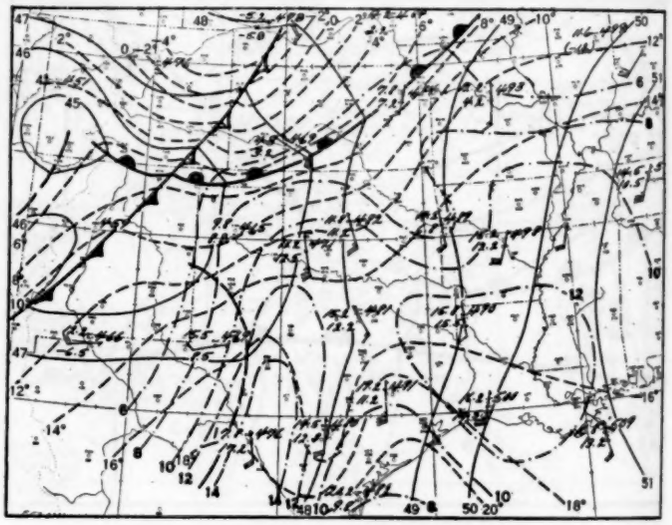

FIGURE 17.—850-mb. chart, 1500 GMT, May 1, 1954.

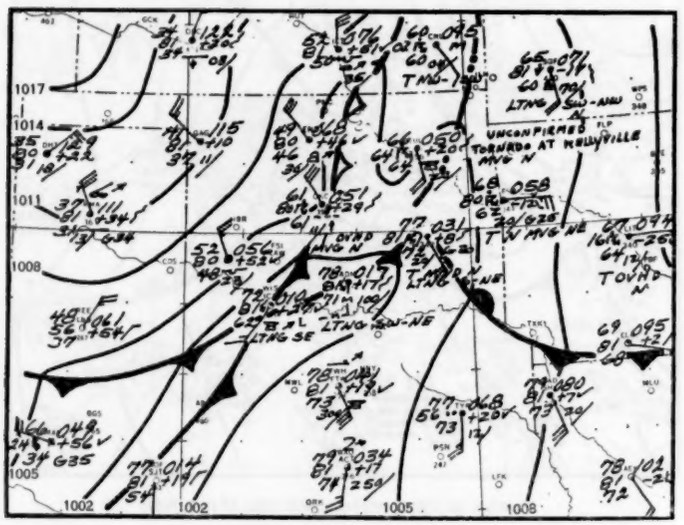

FIGURE 16.—Surface chart, 0330 GMT, May 2, 1954.

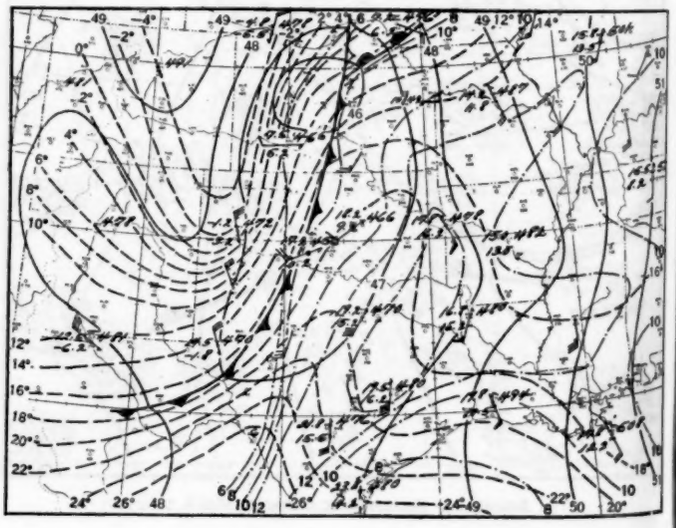

FIGURE 18.—850-mb. chart, 0300 GMT, May 2, 1954.

considerable detail by various authors including Means [2], Crawford [3], Fulks [4], Fawbush, Miller and Starrett [5], and Armstrong [6]. The tornadoes began about midway between the times of figure 17 and figure 18; and it appears that they occurred in the warm tongue, the western portion of the moisture ridge, and west of the low level jet. Considerable data were available at 2100 GMT to substantiate these conclusions.

Coupled with the strong warm, moist air advection in the low levels over Oklahoma was warm air advection to great heights as indicated by the 500-mb. charts (figs. 19 and 20). The magnitude of the warm air advection over Oklahoma preceding the tornadoes on May 1 is shown by the 1000 to 500-mb. thickness pattern (figs. 21 and 22). The strongest warm air advection, as shown by the 1000–500-mb. thickness lines and 700-mb. contours, appeared just southwest of Oklahoma City at 1500 GMT (fig. 21); by 0300 GMT (fig. 22) it had moved through Oklahoma into western Missouri just ahead of the area where tornadoes had occurred.

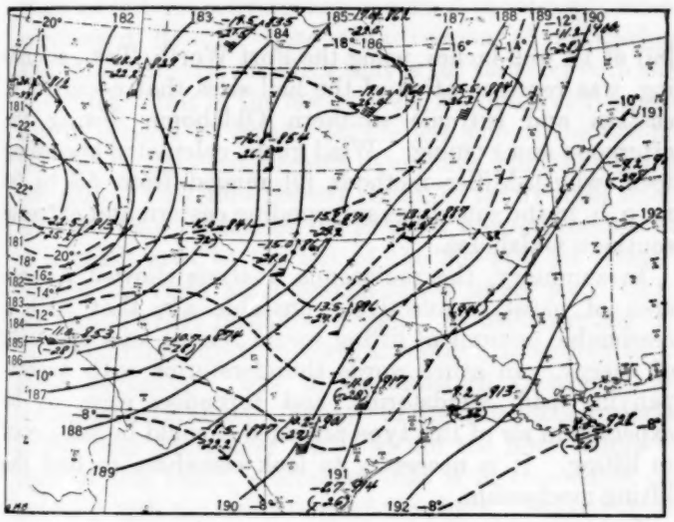

FIGURE 19.—500-mb. chart, 1500 GMT, May 1, 1954.

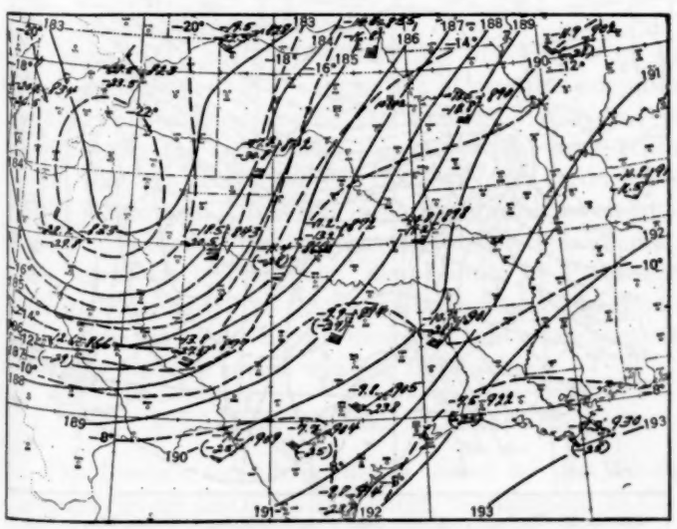

FIGURE 20.—500-mb. chart, 0300 GMT, May 2, 1954.

In connection with the thickness chart, Mook [7] points out that in many multiple tornado outbreaks the 18,600-ft. thickness contour roughly parallels the track of tornadoes. It is interesting to note that on May 1 the 18,600-ft. contour moved over the area close to the time of the tornado occurrences.

THERMODYNAMICS

The method of radiosonde analysis is explained in Appendix I. The results of the analysis are shown in figures 23 and 24. A broad moist tongue with mixing ratios above 8 gm./kg. in the lower 5,000 ft. lay south and east of a line through western Texas, northern Oklahoma, southern Missouri, and central Illinois with a steep moisture gradient on the western side, particularly over western Texas. Low mean lifting condensation levels indicated that very little lifting was required to produce condensation in the moist tongue. Levels of free convection existed over most of the moist air and when compared

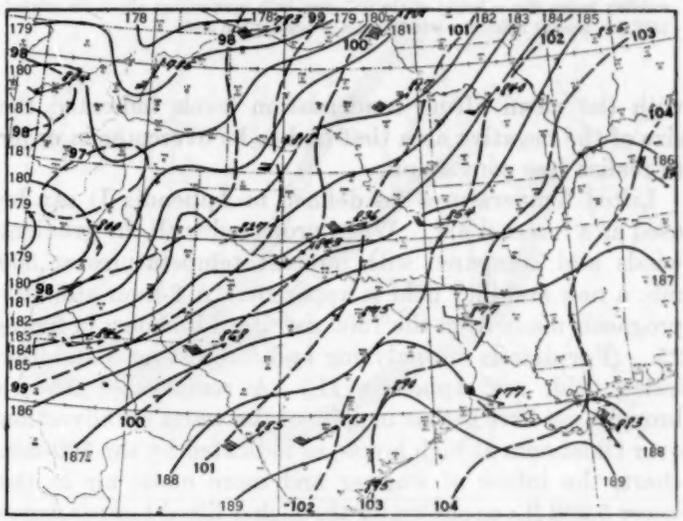

FIGURE 21.—1000-500-mb. thickness chart, (solid lines), and 700-mb. contours (dashed lines), 1500 GMT, May 1, 1954.

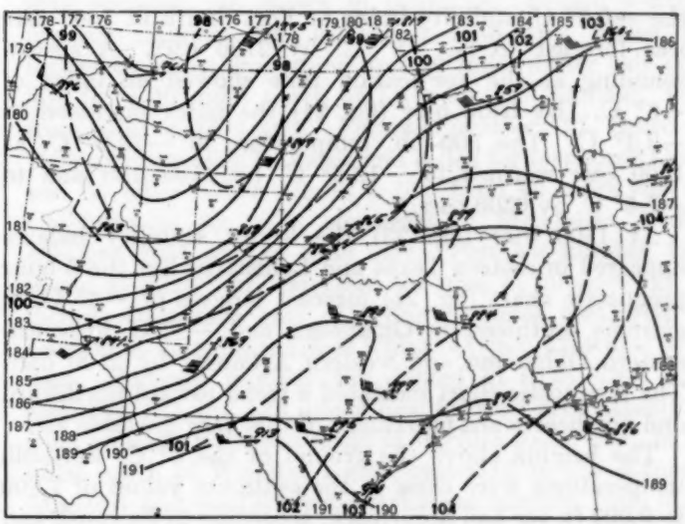

FIGURE 22.—1000-500-mb. thickness chart (solid lines), and 700-mb. contours (dashed lines), 0300 GMT, May 2, 1954.

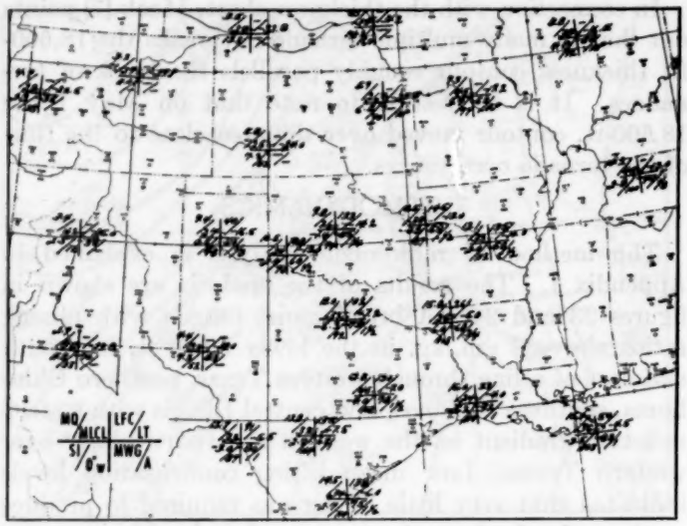

FIGURE 23.—Radiosonde analysis chart, 1500 GMT, May 1, 1954. MQ = mean mixing ratio of the lower 5,000 feet; MLCL = mean lifting condensation level of the lower 5,000 feet; LFC = level of free convection; LT = lifted 500-mb temperature; SI = stability index; 0°w = height of the 0°C. wet bulb temperature above the ground; MWG = forecast maximum wind gust; A = forecast hail size.

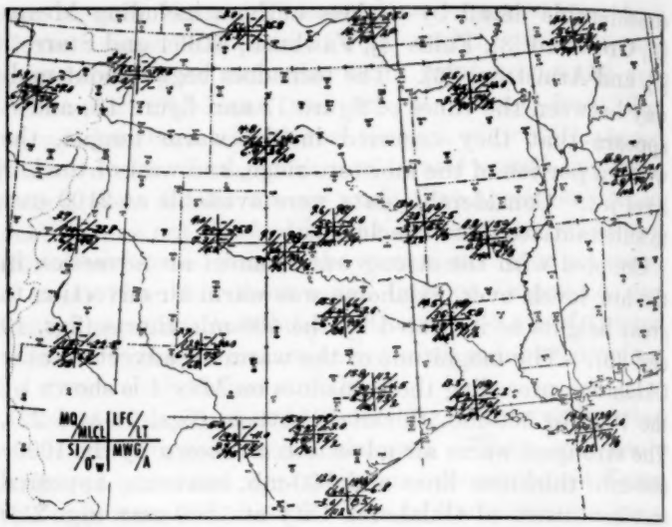

FIGURE 24.—Radiosonde analysis chart, 0300 GMT, May 2, 1954. MQ = mean mixing ratio of the lower 5,000 feet; MLCL = mean lifting condensation level of the lower 5,000 feet; LFC = level of free convection; LT = lifted 500-mb temperature; SI = stability index; 0°w = height of the 0°C. wet bulb temperature above the ground; MWG = forecast maximum wind gust; A = forecast hail size.

with the mean lifting condensation levels indicated the size of the negative area that had to be overcome in order to realize free convection.

Lifted temperatures (as defined in Appendix I) can be used as a forecast aid. When projected with the gradient winds and compared with forecast temperatures at 500 mb. a new stability field is apparent. A 6-hour stability prognosis made from the 1500 GMT data is shown in figure 25. (For details of analyzing and forecasting a stability index field, see Appendix II.) A remarkable feature brought out here is that in spite of the warm air advection over Oklahoma at high levels, as indicated by the 500-mb. chart, the inflow of warmer and more moist air in the lower 5,000 ft., as shown by the higher lifted temperatures upstream, held substantial negative stability indexes over extreme southern and eastern Oklahoma. For example, the −0.8° C. stability index at Fort Smith at 1500 GMT was forecast to be −8° C. by 2100 GMT. A special sounding at the verification time showed an index of −6° C. By 0300 GMT (fig. 24) the index increased to −3.3° C. The 500-mb. temperature of −13.0° C. at 1500 GMT warmed to −12.5° C. by 2100 GMT and to −7.5° C. by 0300 GMT.

At 1500 GMT (fig. 23) the lowest stability indexes appeared in eastern Texas and Louisiana; but the 6-hour prognostic chart (fig. 25) forecast indexes of −3° C. in extreme southwestern Oklahoma, and −8° C. in southeastern Oklahoma and western Arkansas by 2100 GMT. The prognostic chart indicated a trend toward northward and northeastward movement of this very unstable air.

The heights above the ground of the 0° C. wet-bulb temperatures were close to the optimum values of 7,000 to 9,000 ft. for hail occurrence, according to Fawbush and Miller [8]. Calculated hail size (Fawbush and Miller [8]) of 1½ to 2 inches, using the Fort Worth, Tex., sounding, was representative of the hail sizes that occurred in eastern and extreme southern Oklahoma during the afternoon and evening. Wind gusts, calculated according to Fawbush-Miller methods [9] ranged from 55 to 90 m. p. h. in the soundings surrounding eastern and extreme southern Oklahoma.

In summary, the radiosonde analysis showed a large area of moist, convectively unstable air, that with a reasonable amount of lifting would release vast amounts of energy. In other words thunderstorms with accompanying hail, windstorms, and tornadoes were to be expected in air of this type provided it could be subjected to lifting. It is necessary to look elsewhere to find the lifting mechanism.

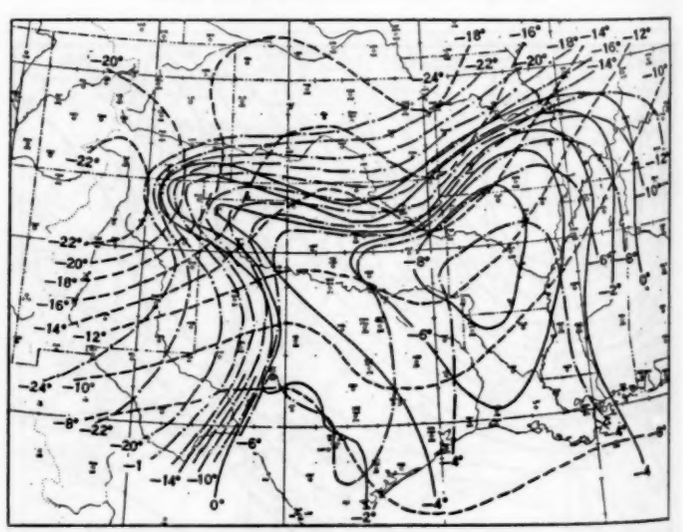

FIGURE 25.—Six-hour prognostic chart of stability index, 2100 GMT, May 1, 1954.

THE LIFTING MECHANISM

Fawbush, Miller, and Starrett [5] suggested that the existence of an axis of high speed winds (jet) at a height somewhere between 10,000 and 20,000 ft. was important to the formation of tornadoes. Beebe and Bates [10] have considered also the jet at the 850-mb. level, and the divergence effects in the region of its intersection with the 500-mb. jet as implied by the vorticity equation. They have also taken into account the effect of a local wind speed maximum along the 500-mb. jet. Because such a maximum was not evident in the tornado area in the May 1 situation, the main emphasis here will be on the effects due to changes in curvature along the jet axes.

The upper and lower jets at 1500 and 0300 GMT are shown in figures 26 and 27. At 1500 GMT there was a splitting of the 500-mb. jet over northern Texas such that over eastern and south central Oklahoma there was advection of cyclonic vorticity, favorable for divergence aloft. The same does not apply to the westward where the left branch curved cyclonically. Along the 850-mb. jet there must have been convergence to permit the straight mostly northward flow in spite of advection of anticyclonic absolute vorticity, an effect that is the same on both sides of the jet. But in the lower levels, frictional convergence will in general be greater on the left side of the 850-mb. jet than on the right, because of cyclonic wind shear on the left side. Therefore the net result, so far as these effects are concerned, indicates the greatest upward motion was in a small area to the left of the 850-mb. jet where it crossed the right hand branch of the upper jet. This is the region where tornadoes began. At 0300 GMT (fig. 27), the maximum effect on vertical motion, according to the same arguments, was in northeastern Oklahoma and southeastern Kansas. The last of the Oklahoma tornadoes ended near McAlester (MLC) within the hour before the time of this chart, a location that is in reasonable consistency with the indications of the chart. In both figures 26 and 27, the jets were not especially well indicated by the data, but were sufficiently so that the results of the method appear encouraging.

Tepper [11] has emphasized the importance of cold front accelerations in the formation of pressure jump lines, which he relates to tornadoes. While no such line was defined (by the writers) on this day in the area, it does seem that the acceleration of the cold front through New Mexico and west Texas was important in the development simply because of the more rapid rate of replacement of the warm air by the cold. Application of Petterssen's trough formula [12] at 1830 GMT indicates acceleration at that time; it seems highly desirable that such computations be made in severe weather forecasting.

WEATHER BUREAU FORECASTS

The forecast tornado areas, as issued by the Weather Bureau Severe Local Storm Center, Washington, D. C., in coordination with District Forecast Centers and other field stations, are shown in figure 28. Severe weather forecast number 126, issued at 1550 GMT, called for tornadoes in an area along and 60 miles either side of a line from 40 miles north of Lubbock to Childress, Tex. from 1700 to 2300 GMT. Forecast number 127, issued at 1925 GMT cancelled this area and called for tornadoes along and 50 miles either side of a line from 40 miles east of Childress to 70 miles southeast of McAlester, Okla., effective 1925 GMT to 0130 GMT. Forecast number 128, issued at 2226 GMT, extended the area in number 127 to include Oklahoma east of a line 40 miles northwest of Lawton to 55 miles north of Tulsa between 2230 and 0300 GMT. Forecast number 129, issued at 0128 GMT, consolidated 127 and 128 into a new forecast area extending from a line 30 miles southeast of Wichita Falls, Tex., to 60 miles north of Wichita, Kans., eastward to the Kansas-Missouri and the Oklahoma-Arkansas borders, from 0126 GMT to 0500 GMT. Every reported tornado in Oklahoma was within a time and area specified by the forecasts.

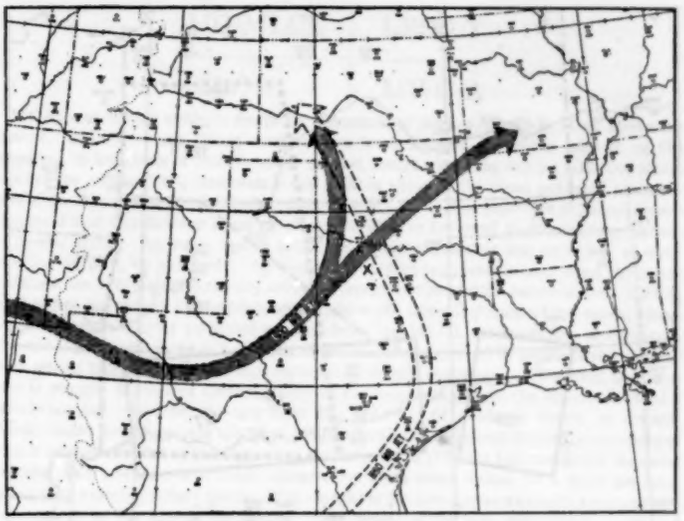

FIGURE 26.—850-mb. and 500-mb. jets, 1500 GMT, May 1, 1954.

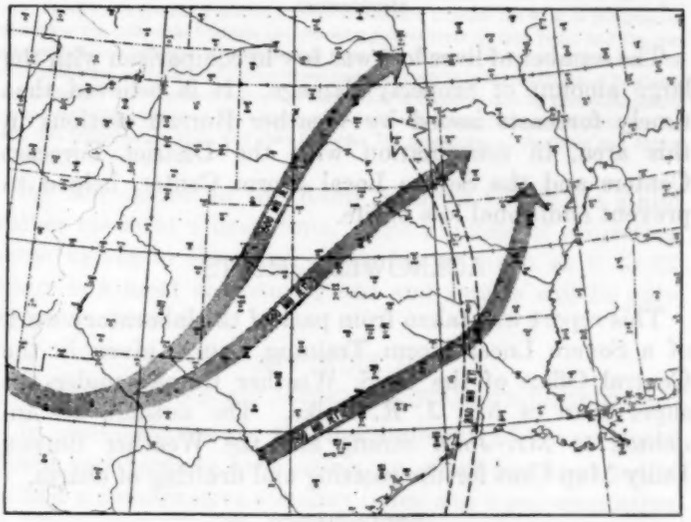

FIGURE 27.—850-mb. and 500-mb. jets, 0300 GMT, May 2, 1954.

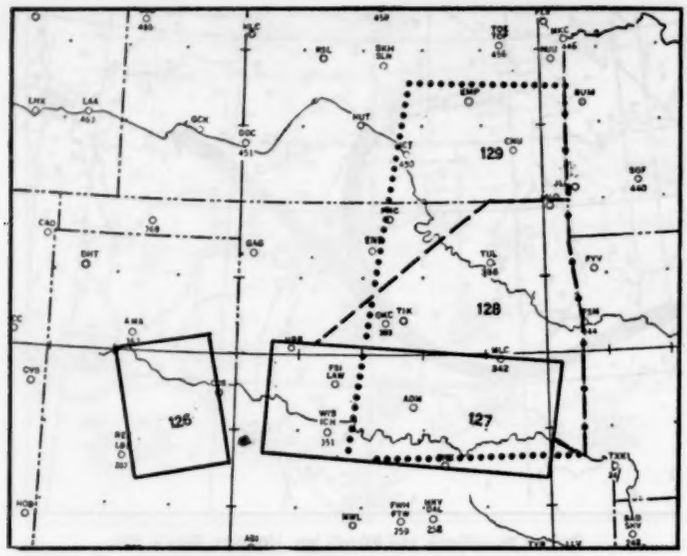

FIGURE 28.—Official Weather Bureau tornado forecast areas, May 1, 1954. See text for identifications.

The number of lives lost was few in comparison with the large amount of property damage. It is believed that timely forecasts issued by Weather Bureau stations in this area, in coordination with the District Forecast Centers and the Severe Local Storm Center, helped to prevent additional loss of life.

ACKNOWLEDGMENTS

This report was taken from part of the laboratory work of a Severe Local Storm Training Course given in the Central Office of the U. S. Weather Bureau under the supervision of Mr. J. R. Fulks. The authors are indebted to Mr. John Strong and the Weather Bureau Daily Map Unit for the plotting and drafting of charts.

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APPENDIX I

A RADIOSONDE ANALYSIS FOR SEVERE LOCAL STORM AND TORNADO FORECASTING

Severe local storm and tornado forecasting requires a

comprehensive analysis of the upper air soundings, especially in and around a possible threat area that may be outlined from the general synoptic situation. There are many ways to obtain this analysis; and it may be difficult in the end to say that one is better than the other. There are, however, certain general features that must be incorporated. Certainly, every analysis needs to include a measure of thermal stability, moisture content, and potential energy. In addition, the operation should be standardized so that a number of forecasters can go through the procedure and come out with very nearly the same answers. Time is essential in the preparation of the forecast, and the radiosonde analysis should not be so long that time is sacrificed from other equally important work. Finally, the resulting information should be plotted on a chart for ready reference and for comparison of one station with another.

A suggested type of radiosonde analysis is presented here that seems practical enough to be incorporated into the routine of daily forecasting. The first step is to draw the wet-bulb temperature curve on the adiabatic charts. It then becomes very easy to determine convective stability. Next, draw a horizontal line at a height of 5,000 ft. above the ground; the selection of this height is based on the approximate height of the mean moist layer in the Fawbush–Miller mean tornado sounding [13]. In the past, emphasis has been placed on the actual height of the low-level moist layer for computations. Often it is difficult to define a moist layer; different forecasters may choose different heights. Also, studies by Armstrong [6], Malkin and Galway [14], recent work by Fawbush and Miller [15] and Beebe [16] point out that tornadoes sometimes occur in air that is moist to very high levels. Beebe and Bates [10] and Means [17] show that moisture is carried to higher and higher levels when the air mass undergoes low level horizontal convergence. Therefore the exact height of a moist layer becomes less important. It is not intended here to discount the importance of the dry-over-moist airmass structure. It is this structure, with the inversion over the moist air, that will permit great amounts of potential energy to be stored. This is indicated by positive areas observed on the adiabatic charts with large negative stability indexes (Showalter [18]). This inversion acts as a lid to convective activity; but if removed by a lifting or "triggering" mechanism the possible generation of kinetic energy is tremendous. On the basis of thermodynamical reasoning alone it is the authors' opinion that perhaps the most severe tornadoes can be expected in air that has built up a large amount of potential energy by dry-over-moist structure before the "triggering mechanism" (such as the arrival of a squall line) begins to carry moisture high enough for it to reach the level of free convection.

A suggested model for this raob analysis is as follows:

MQ/MLCL	LFC/LT
SI/0° w	MWG/A

MQ=mean mixing ratio, in grams per kilogram, of the lower 5,000 ft. of air above the ground. MLCL=mean lifting condensation level through the lower 5,000 ft. of the sounding, in hundreds of feet above the ground, found where the mixing ratio line representing the value of MQ intersects a dry adiabat through the mean potential temperature of the lower 5,000 ft. It is believed that the MLCL is representative of the condensation level that will develop in an air mass subjected to low-level horizontal convergence or frontal lifting. Its value can be improved, when forecasting late afternoon or early evening activity, by forecasting the maximum surface temperature and using the intersection of the MQ line with the dry adiabat through the maximum temperature. LFC=level of free convection in hundreds of feet above the ground, if such a level exists, found where a pseudo-adiabat projected upward from the MLCL intersects the temperature curve. Heights are given in hundreds of feet above the ground to facilitate comparison with ceiling heights and cloud tops reported in hourly sequences. LT=lifted temperature at 500 mb. in degrees Celsius, found at the intersection with the 500-mb. level of a pseudo-adiabat projected upward from the MLCL. SI=stability index, in degrees Celsius found by subtracting the lifted temperature from the actual 500-mb. temperature. This is a slight revision of the Showalter Stability Index [18], but has essentially the same meaning. In addition, it is more conservative since mean values for a layer are used rather than values at a fixed point. 0° w=height of the zero-degree wet-bulb temperature, in hundreds of feet above the ground. The height of the zero wet-bulb temperature appears to have a definite relationship to the severity of hailstorms and possibly the occurrence of tornadoes (*cf.*, Showalter [18]). The optimum height seems to fall around 7,000 to 9,000 ft. (Fawbush and Miller [8]). MWG=maximum wind gusts, in miles per hour, found by projecting a pseudo-adiabat downward through the 0° w to the ground, measuring the difference between the resulting temperature at that point and the surface temperature expected at the forecast time of occurrence of the thunderstorm, the maximum wind gust then to be determined from the Peak Wind Gust Graph of Fawbush and Miller [9]. A=expected hail size at the ground in inches, found by first determining the convective condensation level (intersection with the temperature curve of the mixing ratio line representing MQ), and then following the procedures of Fawbush and Miller [8] using their hail graph.

All the values on the Raob Analysis Chart are static values taken at a fixed time. The problem of projecting these values in time and space for as much as 6 to 12 hours is a most challenging one and results will be only approximate at best.

APPENDIX II

ANALYZING AND FORECASTING THE STABILITY INDEX FIELD

In connection with the development of severe local storm and tornado forecasting, an effort has been made to find a conservative stability index and a representative stability pattern. The stability index obtained by the Showalter [18] method uses temperature and dew point at one level, either 850-mb. or the top of the moist layer (if below the 850-mb. level), to determine a lifted 500-mb. temperature. It is proposed here to use the mean wet-bulb potential temperature of a layer of air near the surface for the same purpose. The index field may be obtained by graphical subtractions after drawing isolines of the actual and lifted 500-mb. temperatures. A 6-hour prognostic chart may be made by advecting the lifted temperature and the 500-mb. temperature with the wind streams at the gradient level and the 500-mb. level respectively.

Suggested detailed steps in the analysis are:

1. Plot the barbs and shafts for the 500-mb. or 18,000-ft. wind and the gradient level wind (third group in the upper wind message, at an average height of about 2,000 ft. above ground). Plot the raob data around the station circle as follows:

TT hhh
○
T′T′ SI

hhh=height of the 500-mb. surface
TT=500-mb. temperature
T′T′=lifted 500-mb. temperature. When forecasting for late afternoon activity the lifted temperature is based on the forecast surface maximum temperature for the day.
SI=(TT−T′T′)=stability index

2. Draw the isolines:
TT for every two degrees, in red
T′T′ for every two degrees, in green
SI for every two degrees in blue, obtained by graphical subtraction of the two temperature fields.
500-mb. contours in yellow for every 100 or 200 feet, especially when wind reports are scarce.

This analysis would be laborious and tedious for an area as large as the United States; however, its use is intended for smaller threat areas of severe local storm activity and it is usually sufficient to consider only areas with index values less than +4.

A 6-hour stability prognosis may be constructed as follows:

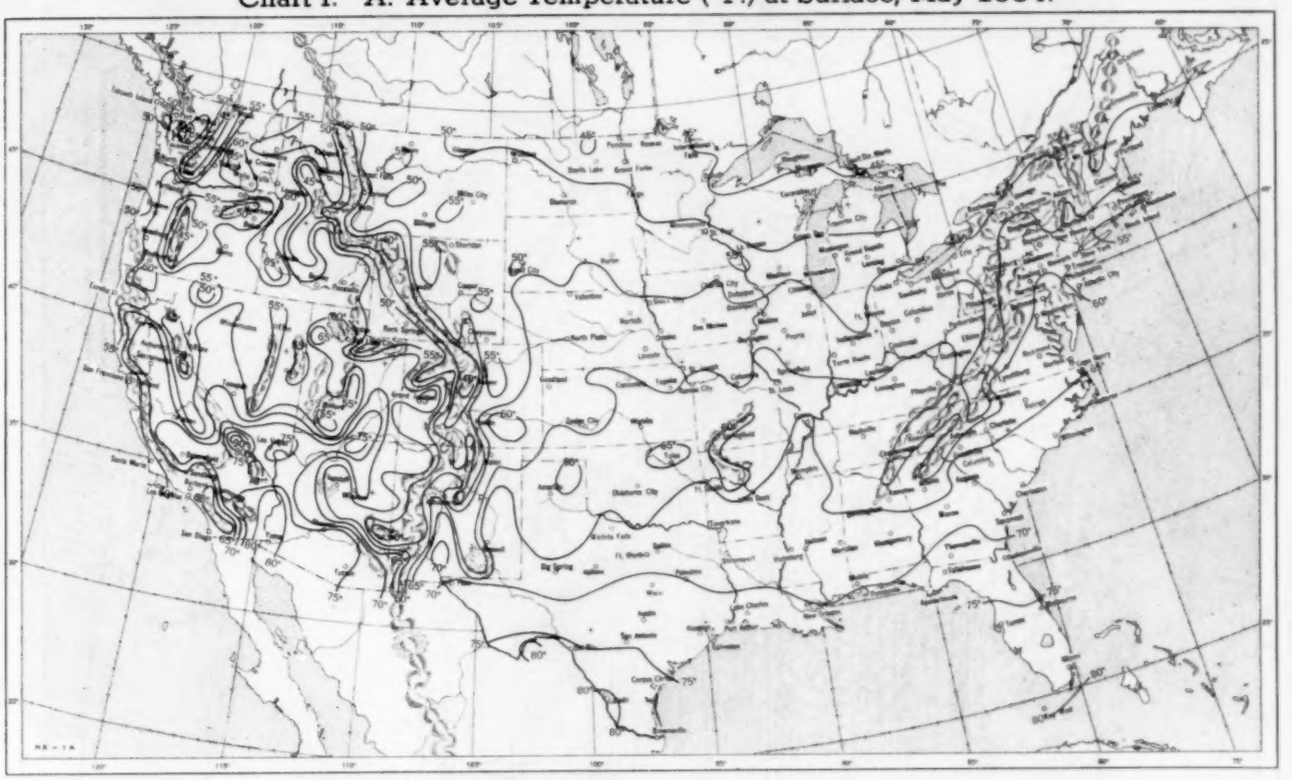
1. Project the 500-mb. temperatures downstream with about 50 percent of the 18,000-ft. or 500-mb. wind speeds, corrected for trough movements, dynamic effects, etc.

2. Project the lifted temperatures downstream with the full speed of the gradient level wind. Since the lifted temperature is based on average conditions through the lower 5,000 ft., it is a fairly conservative property, except as it is affected by diurnal temperature changes and precipitation. Adjustments may be made for frontal movements and expected change in the low level flow.

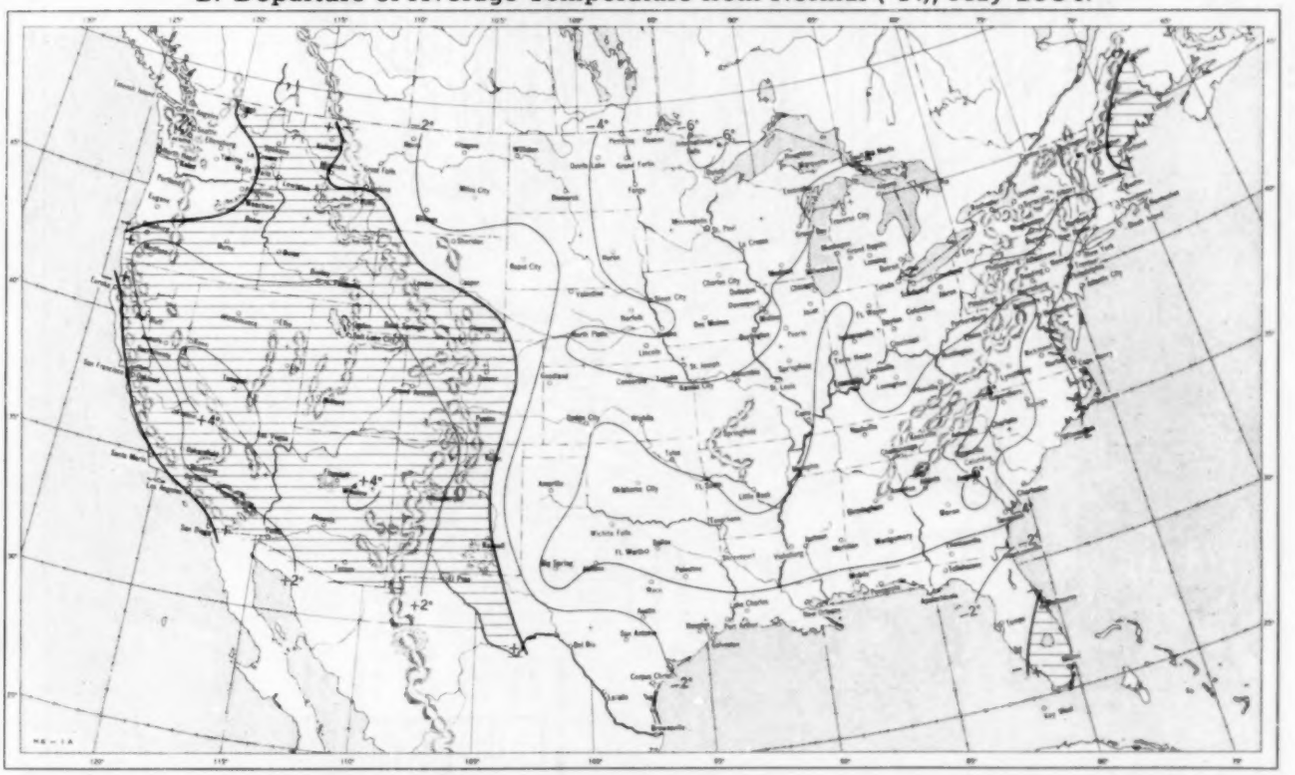
3. Obtain the forecast stability pattern by graphical subtraction. Normally areas with index values greater than +2 can be ignored. The stability index is only a measure of potential energy in the air mass; some lifting or "triggering" mechanism is needed to release the energy. This mechanism may be daytime heating, cold front action, arrival of a squall line, nocturnal cooling aloft, frictional convergence within a zone of cyclonic wind shear or a low pressure center or trough, larger scale convergence and divergence patterns favorable to general lifting, or lifting by a pseudo-cold front formed by previous thunderstorms, and other possible causes.

U. S. GOVERNMENT PRINTING OFFICE: 1954

Chart I. A. Average Temperature (°F.) at Surface, May 1954.

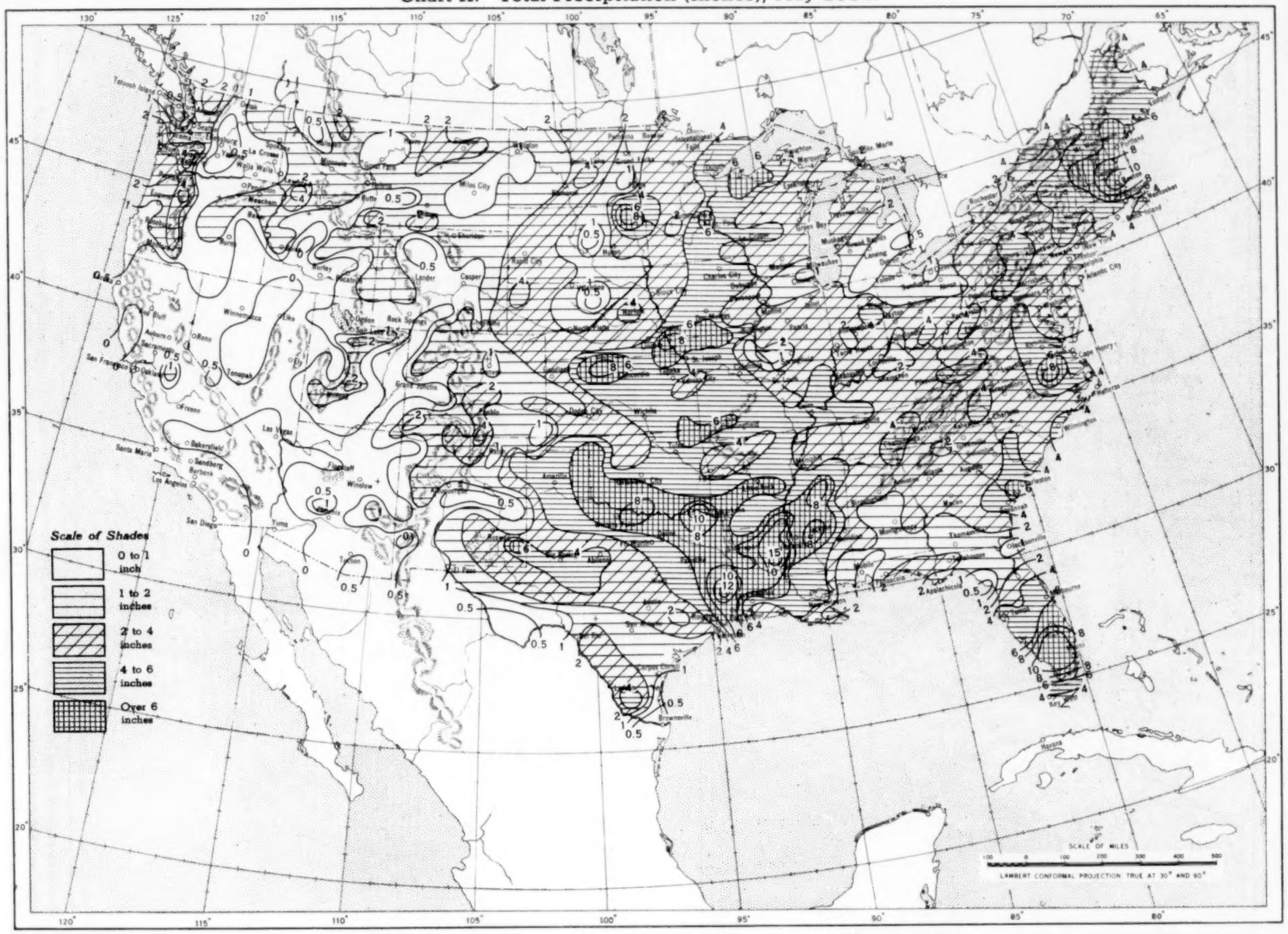


B. Departure of Average Temperature from Normal (°F.), May 1954.



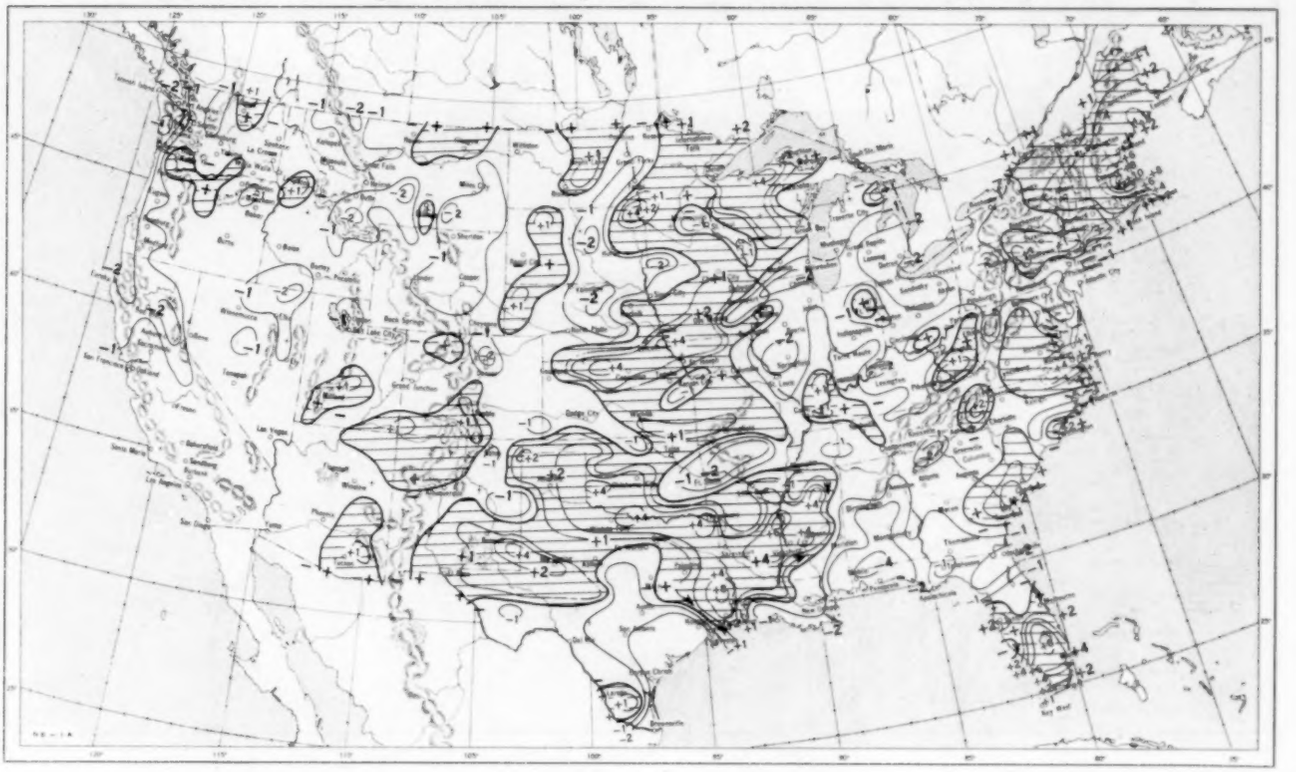
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), May 1954.

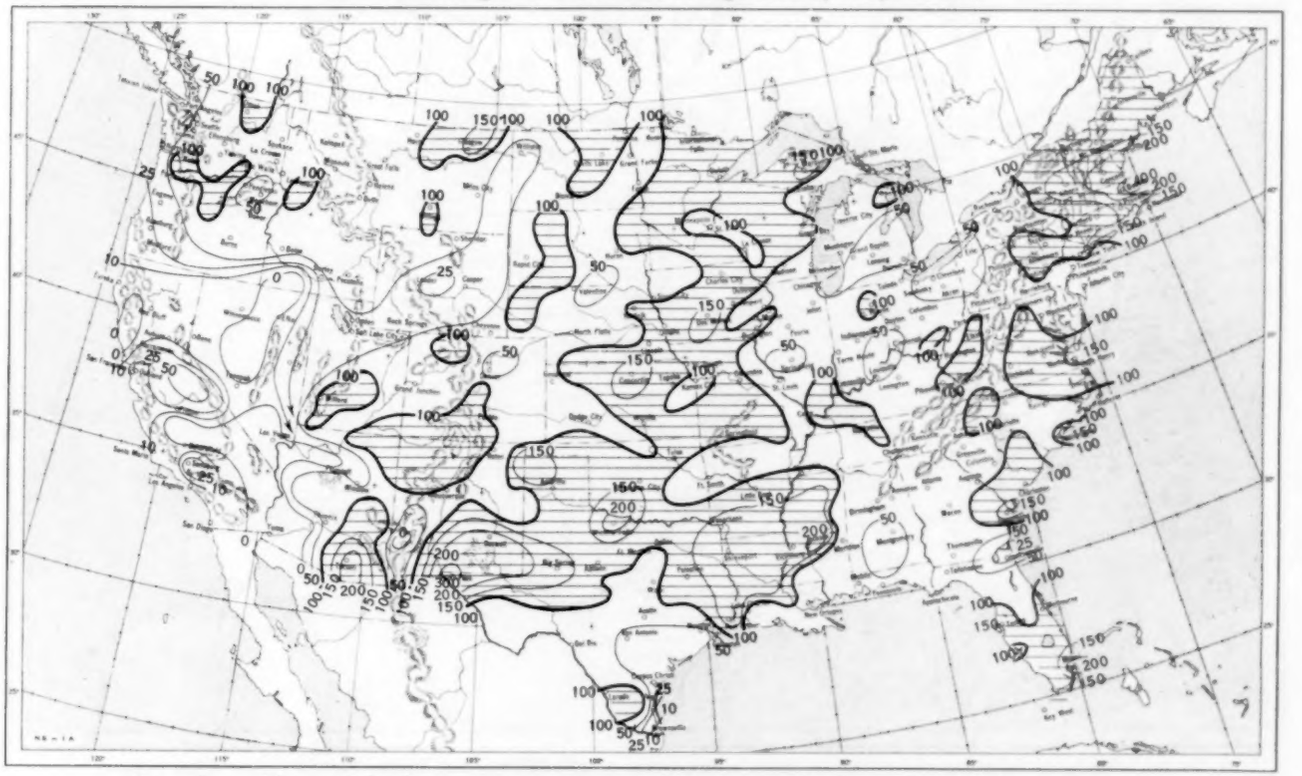

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), May 1954.

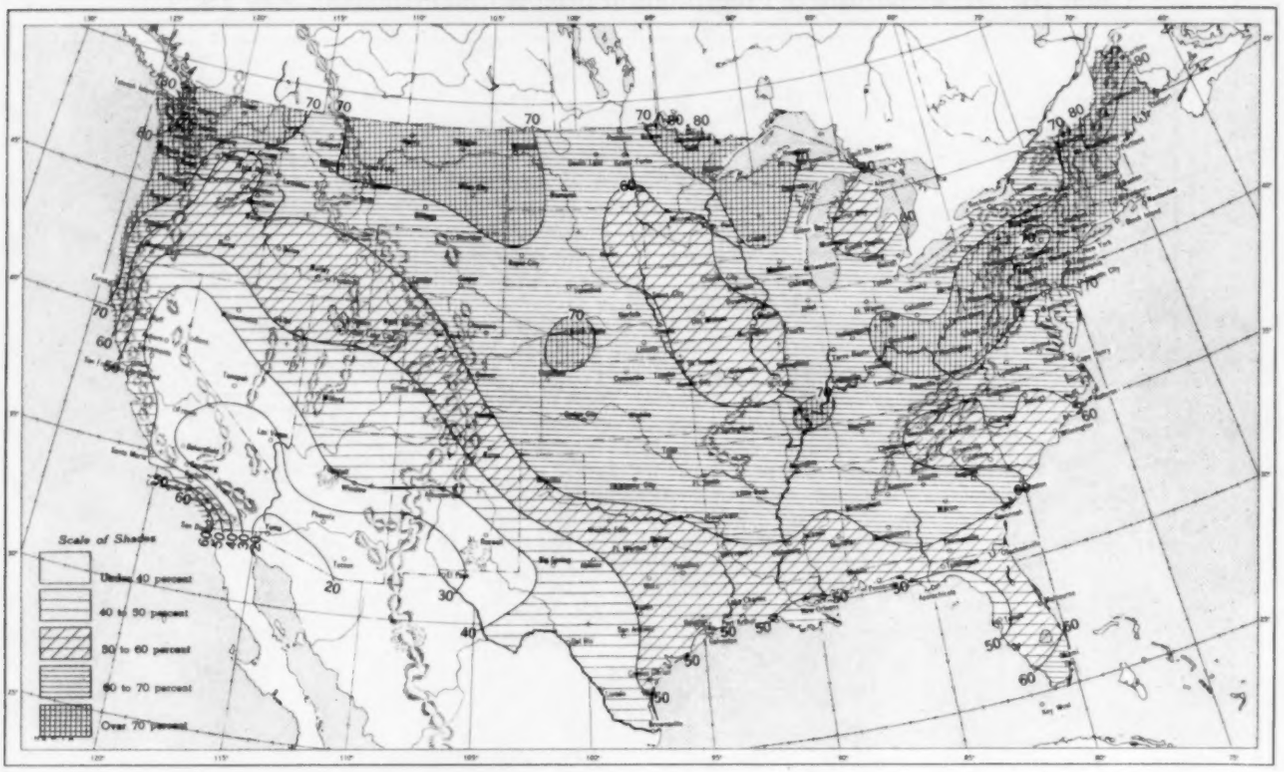


B. Percentage of Normal Precipitation, May 1954.

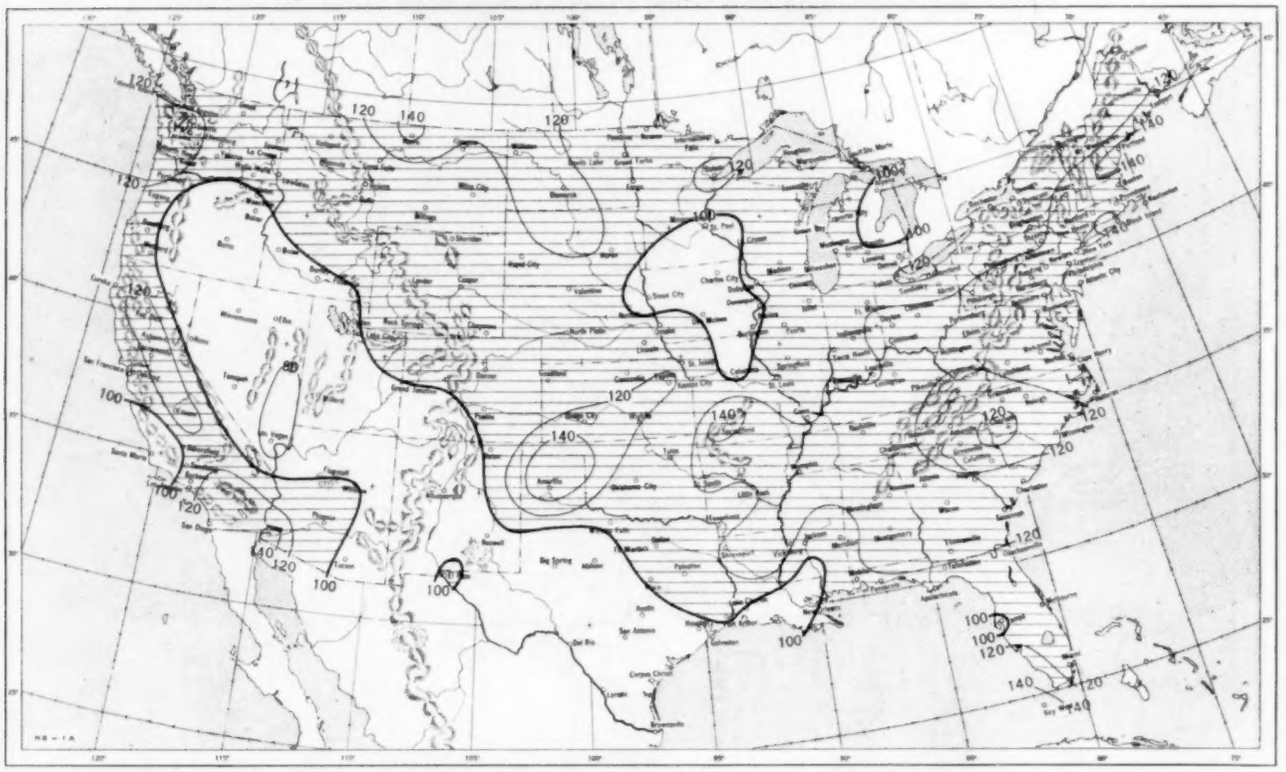


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, May 1954.

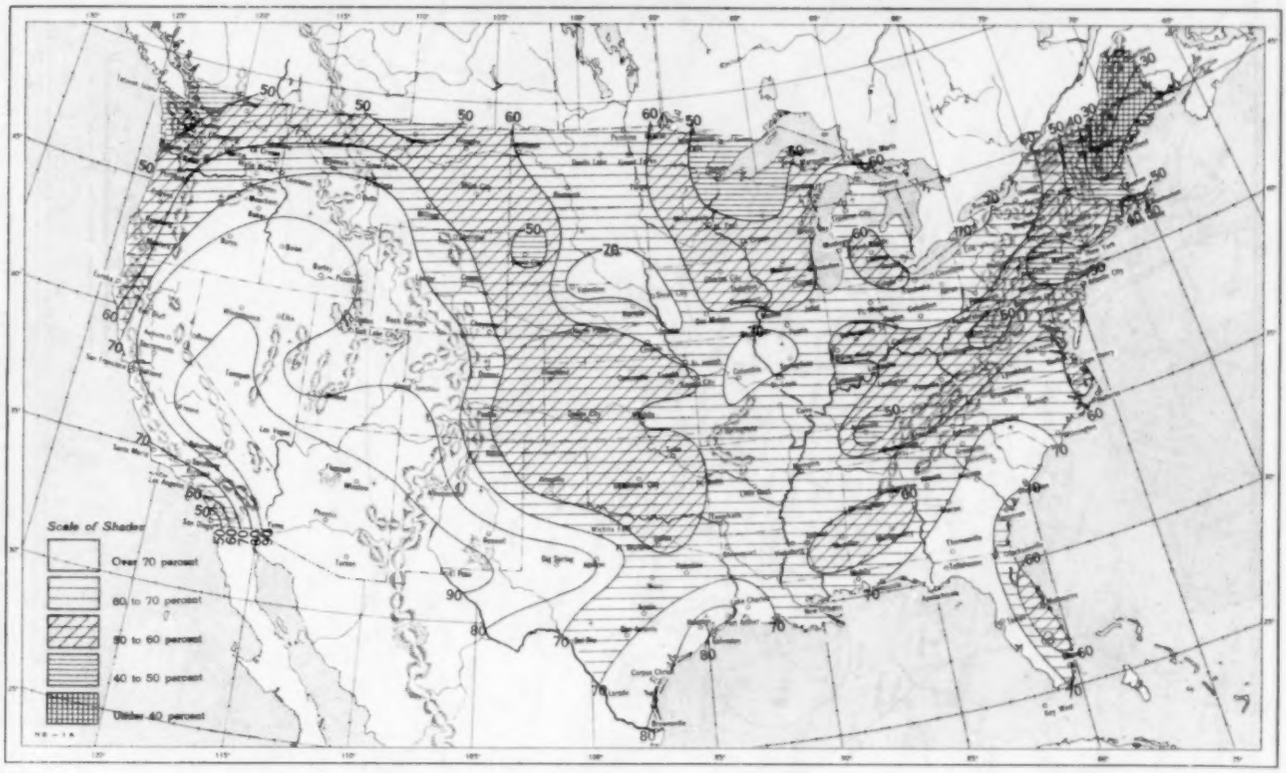


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, May 1954.

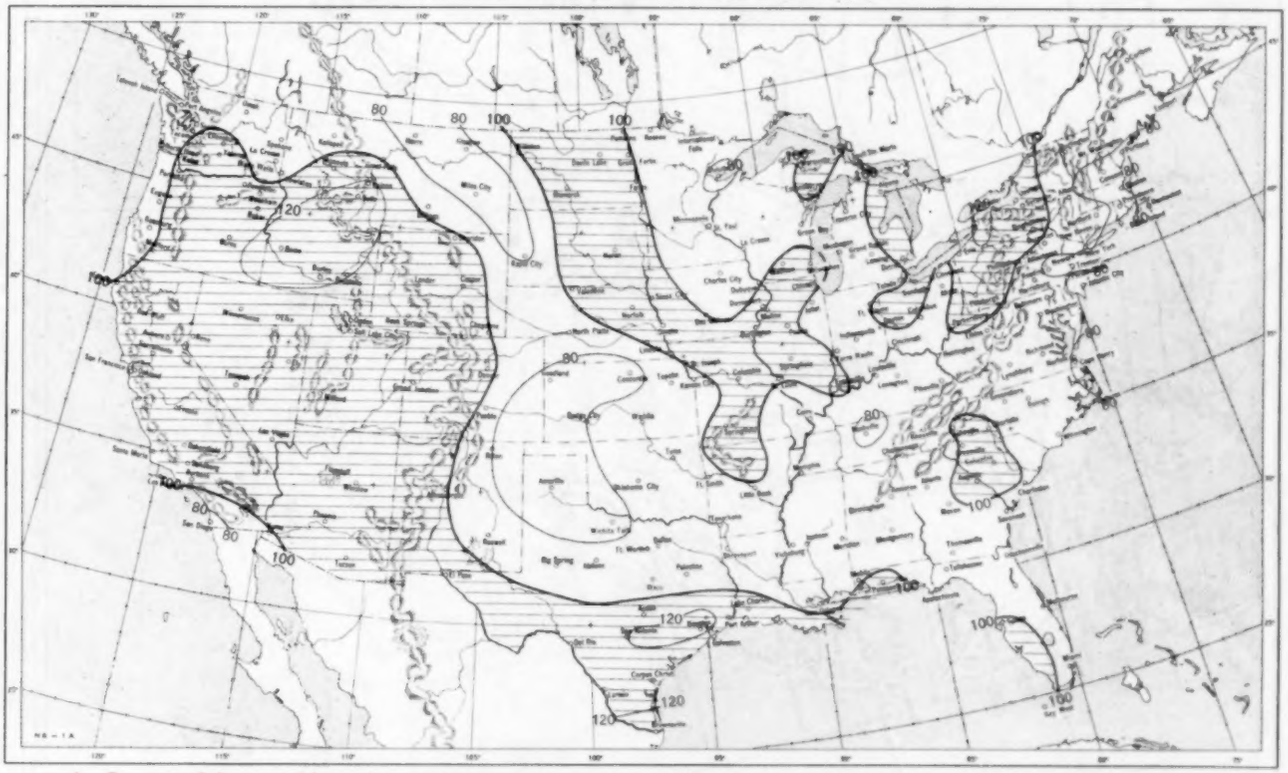


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, May 1954.



B. Percentage of Normal Sunshine, May 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, May 1954. Inset: Percentage of Normal Average Daily Solar Radiation, May 1954.

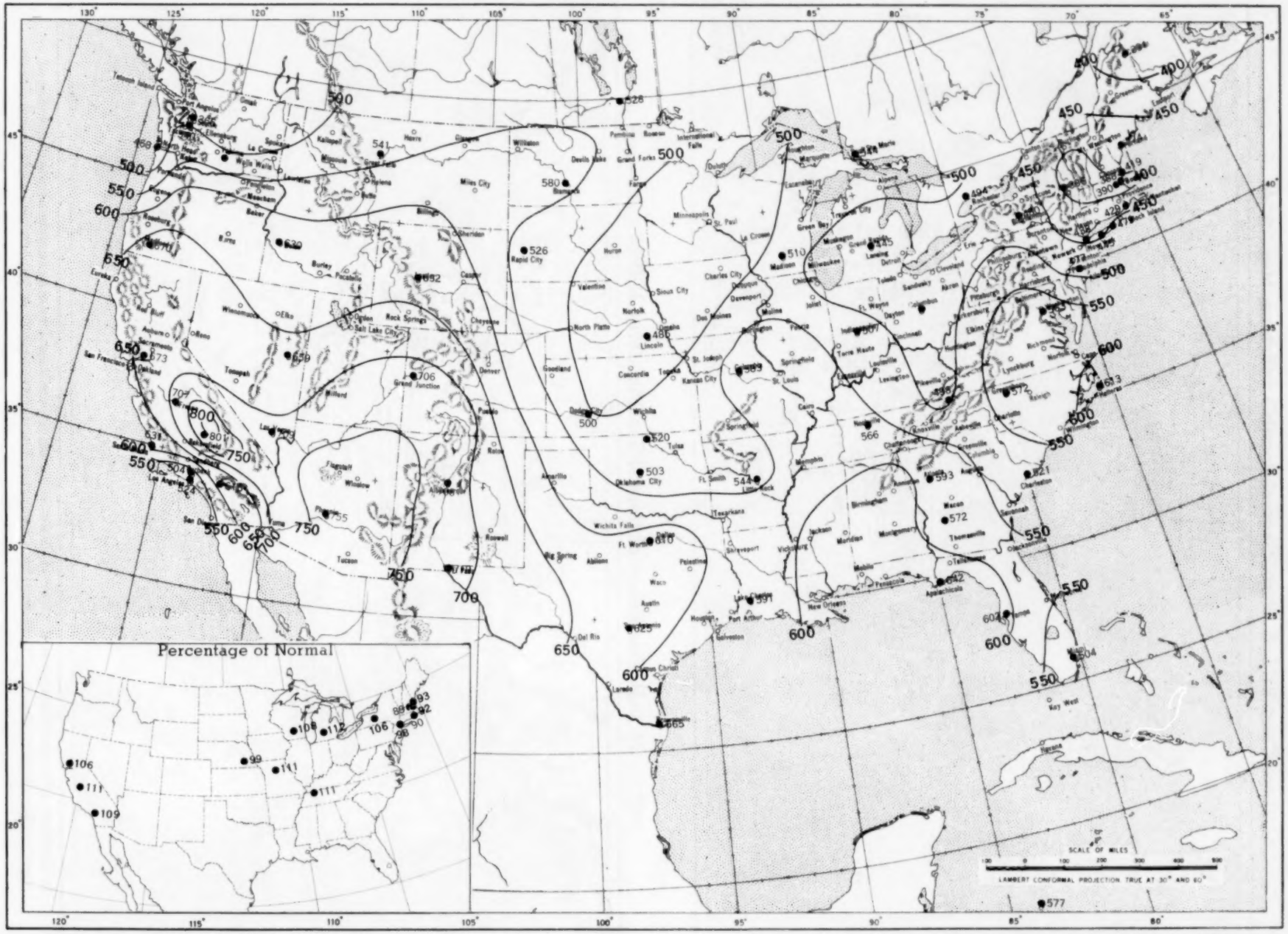
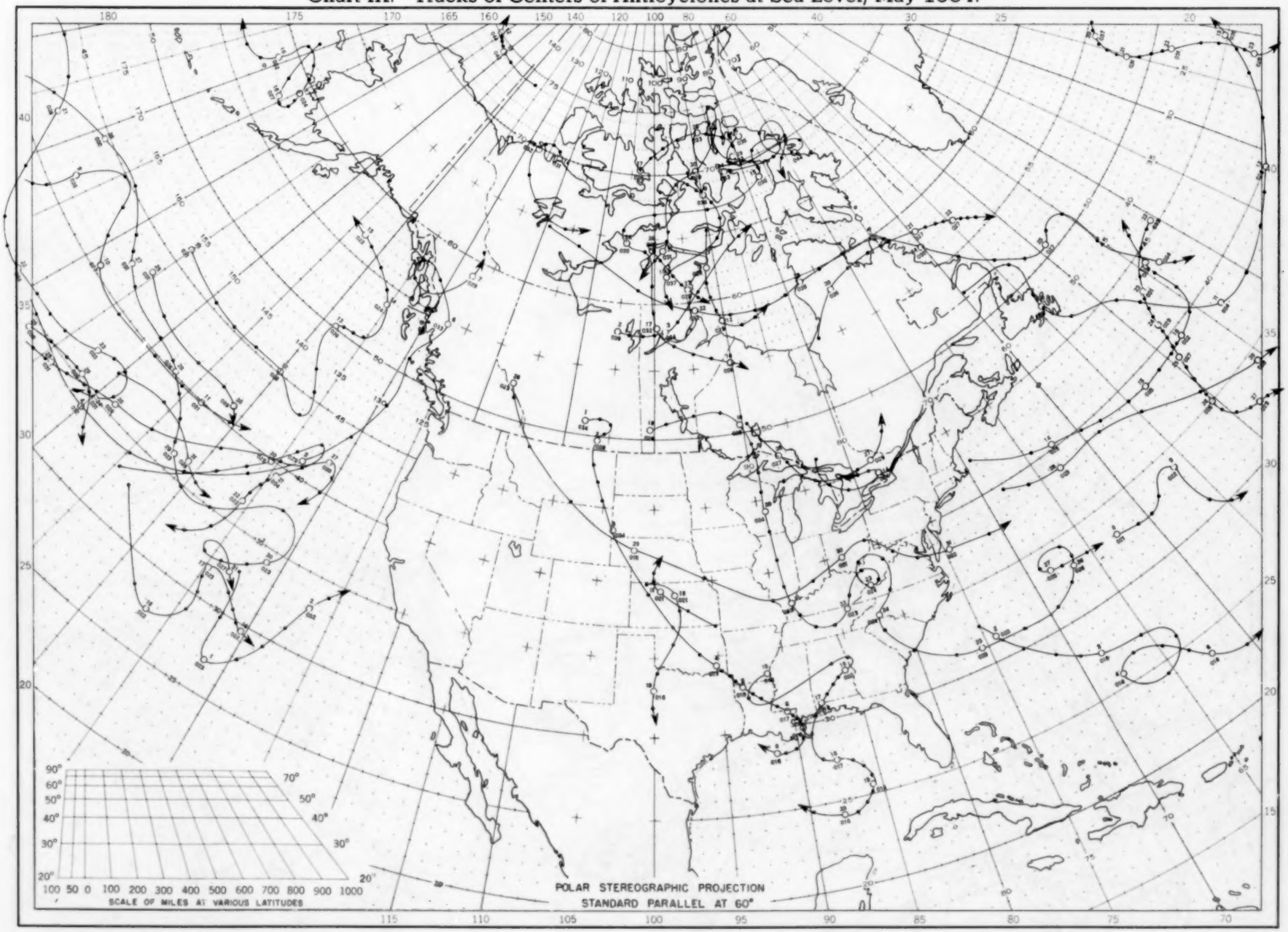


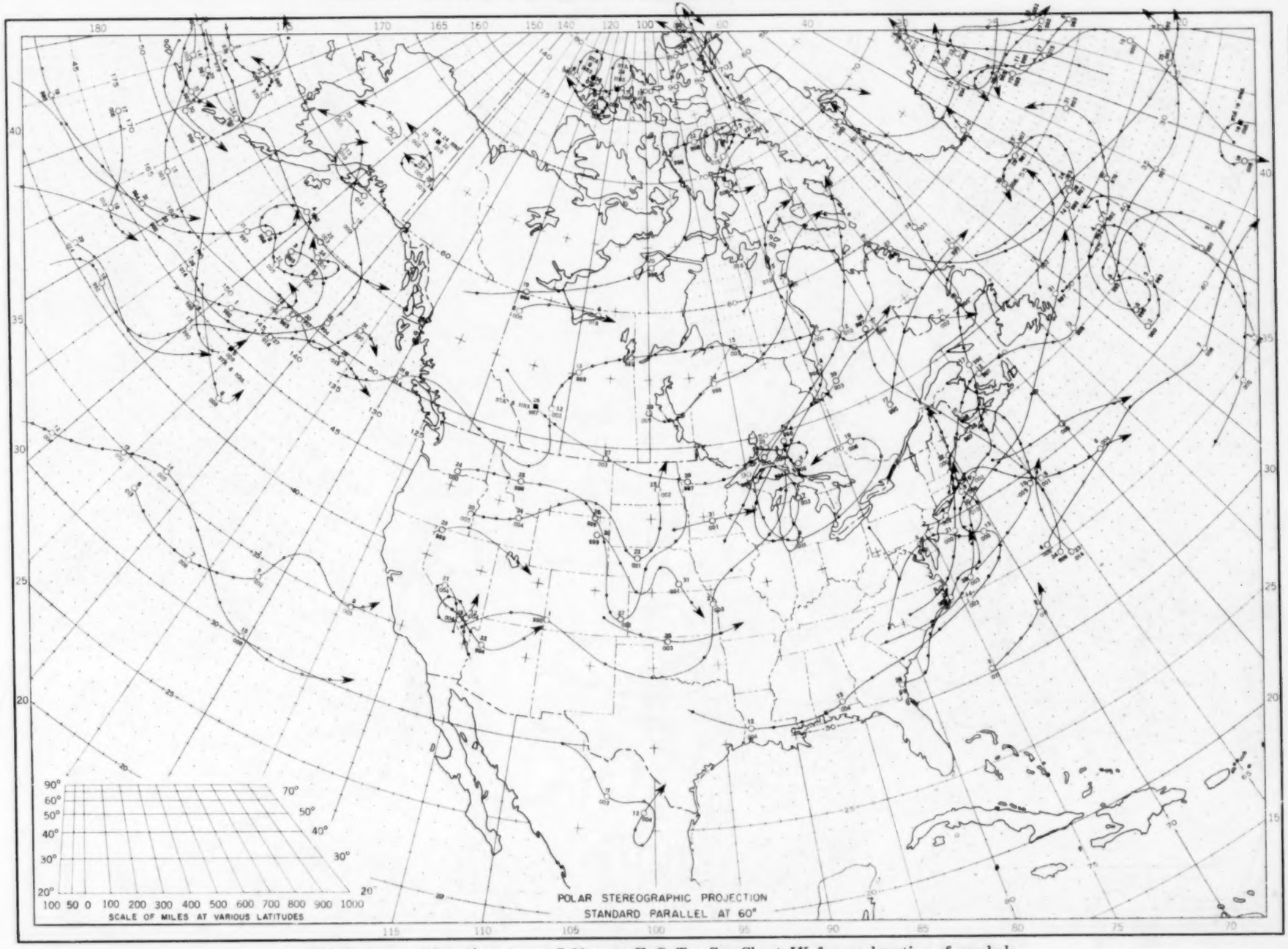
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, May 1954.



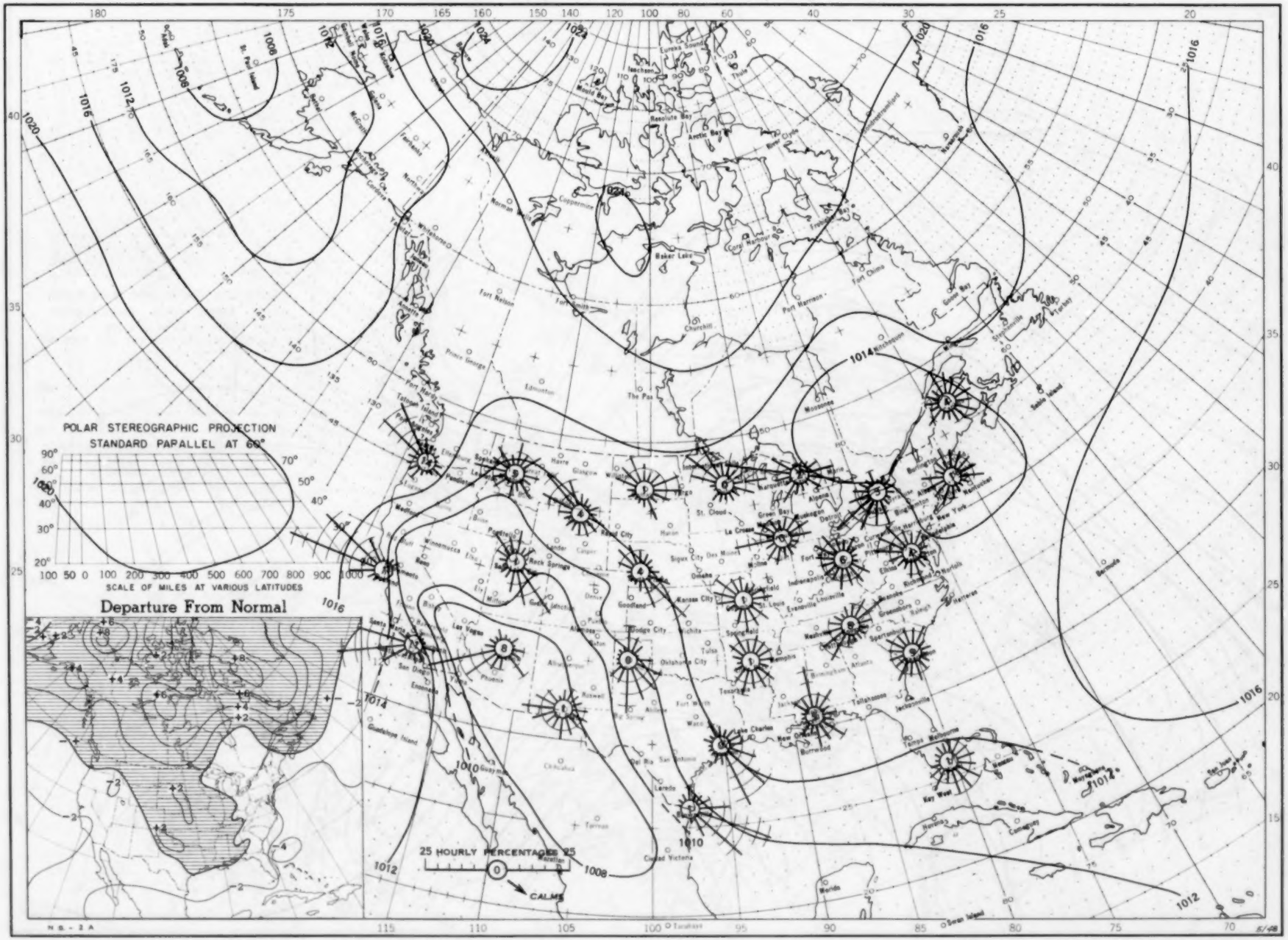
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, May 1954.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

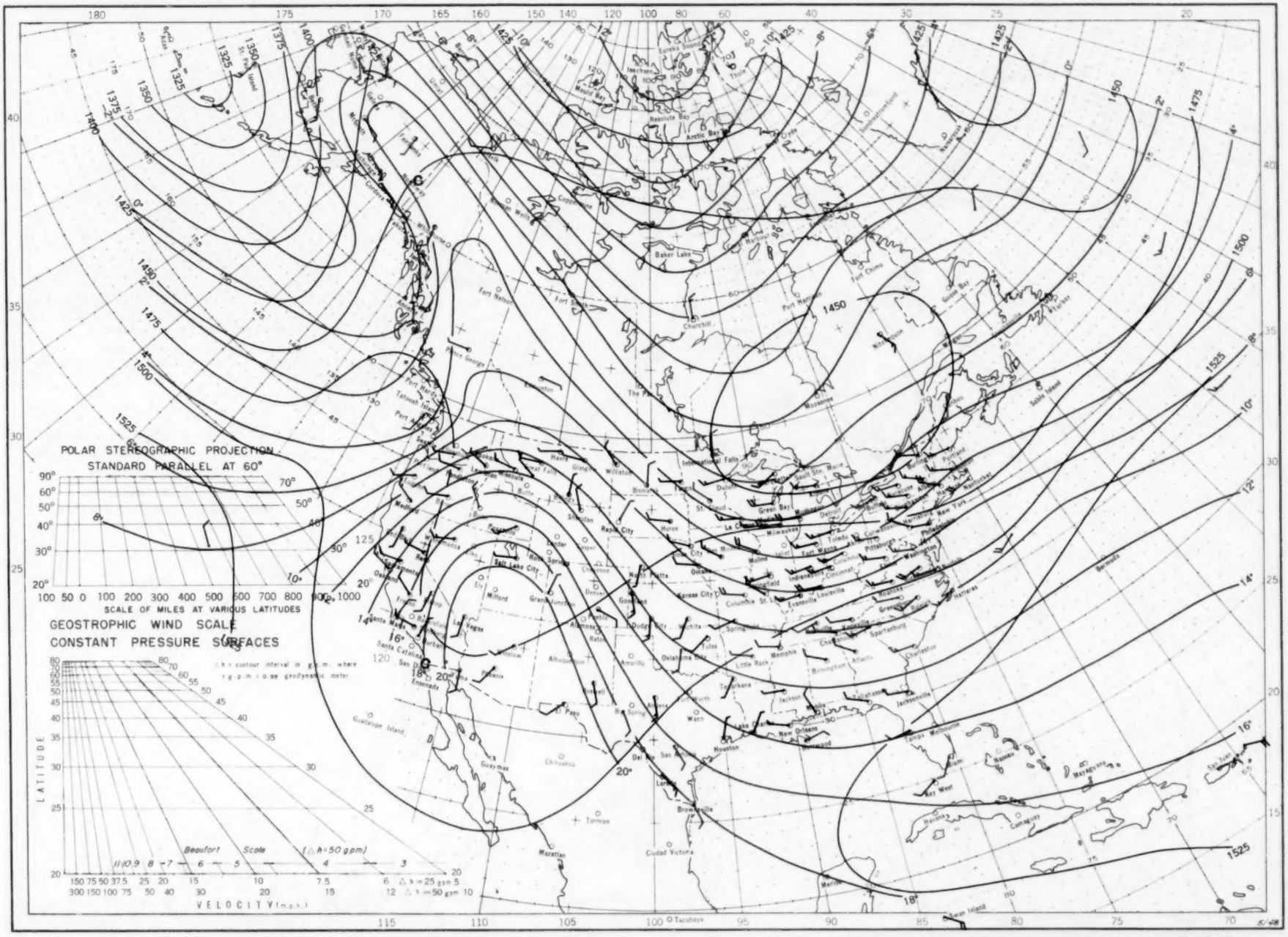
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, May 1954. Inset: Departure of Average Pressure (mb.) from Normal, May 1954.



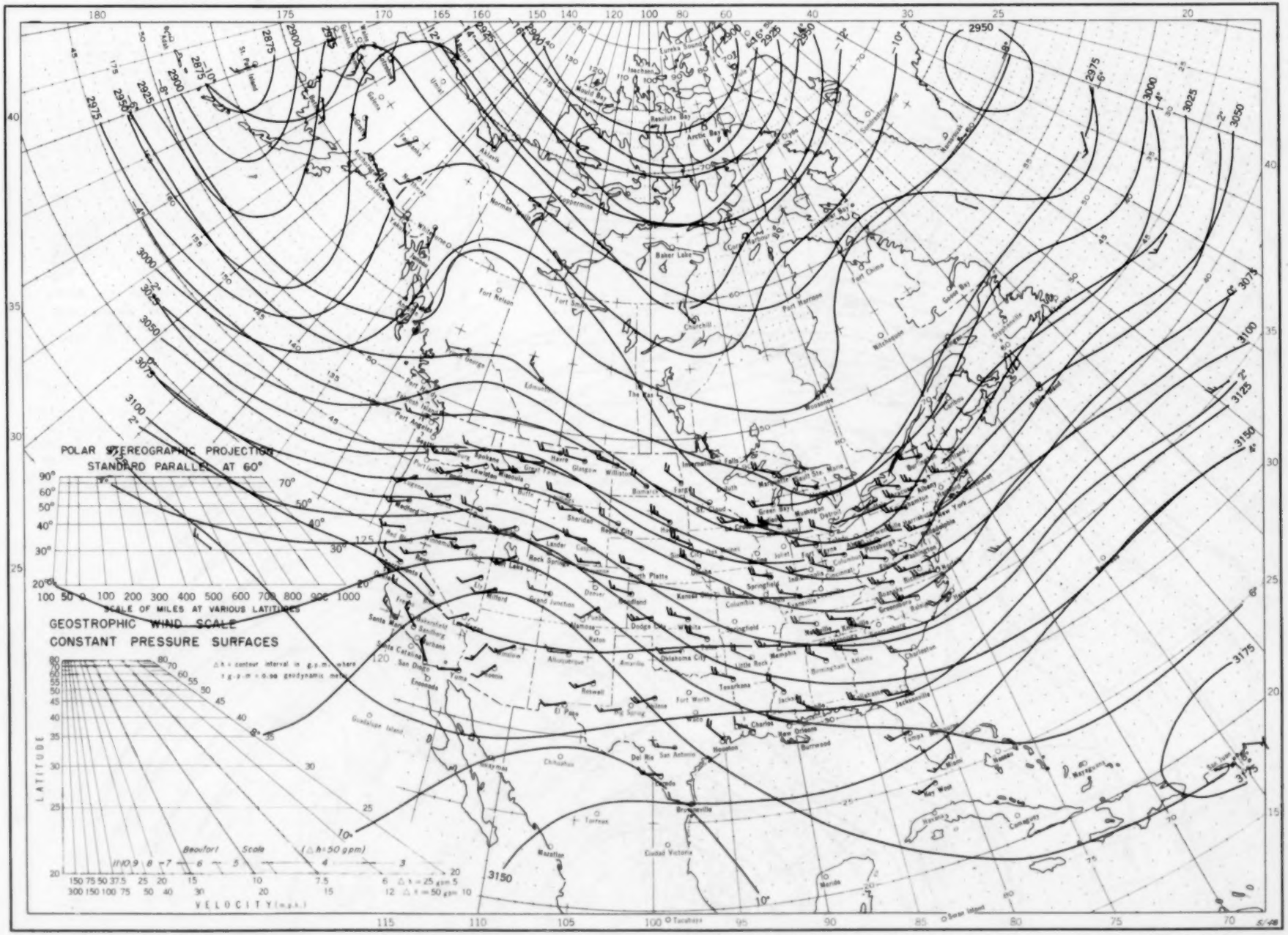
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), May 1954.



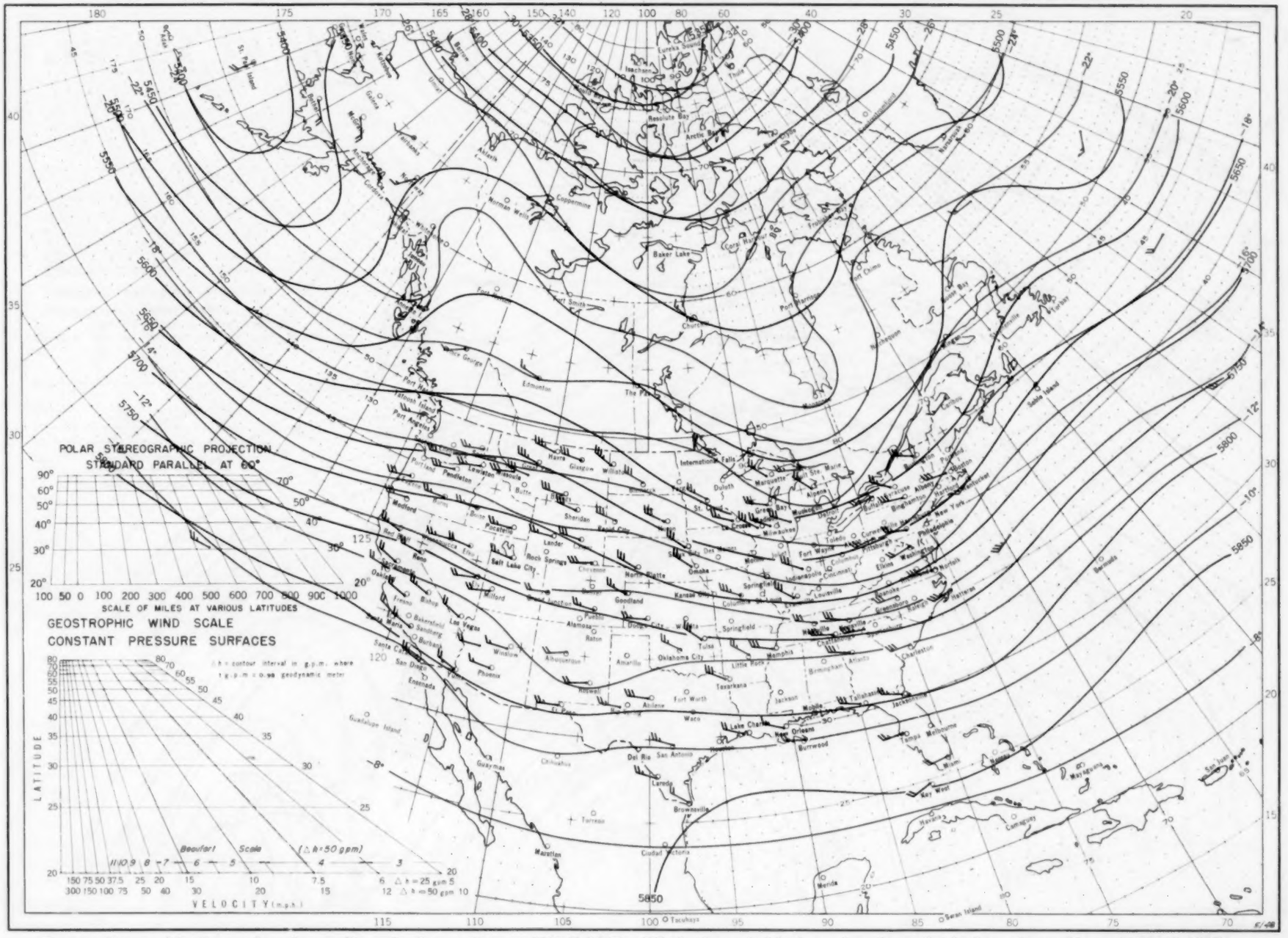
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), May 1954.



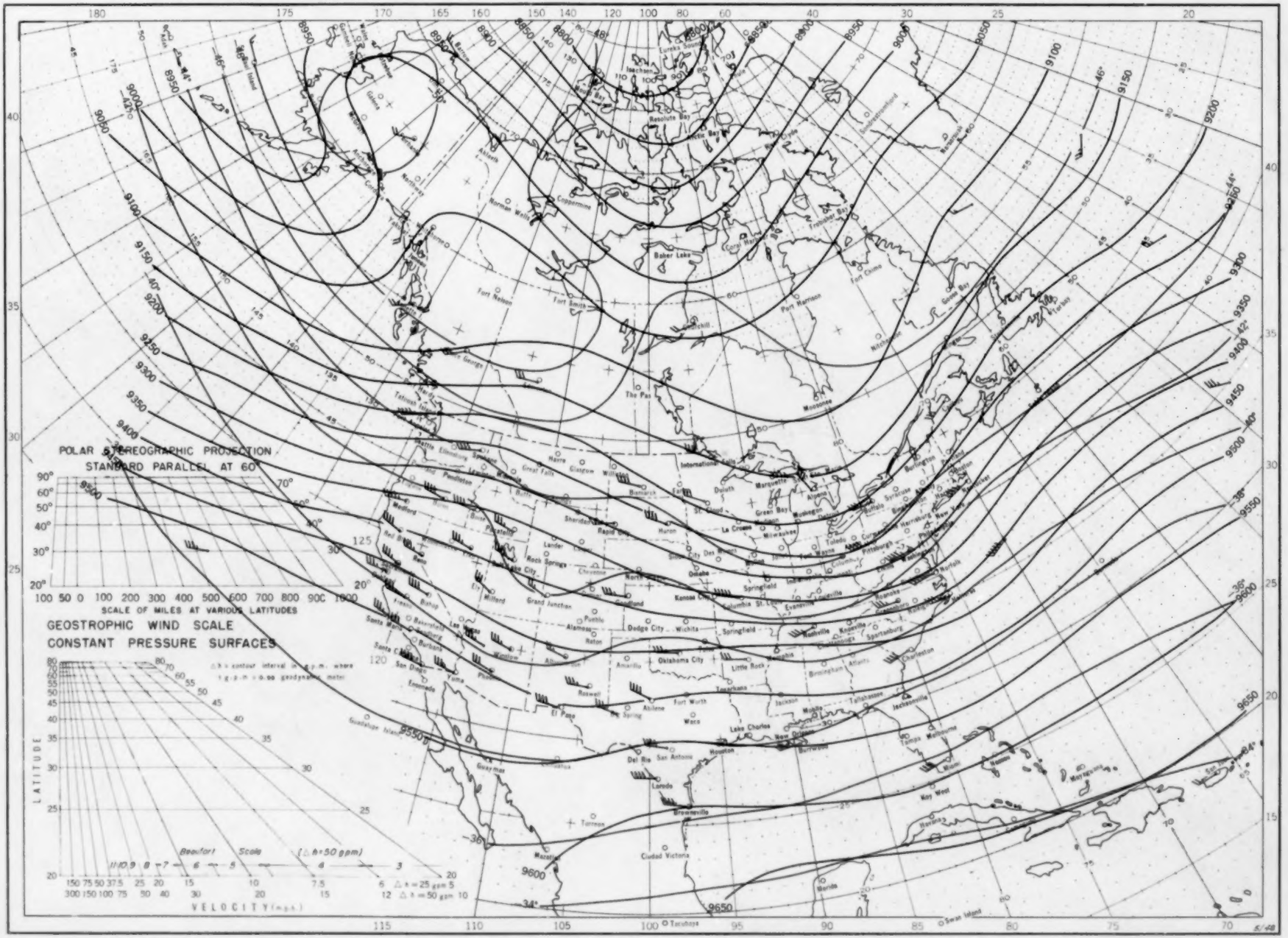
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), May 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. those shown in red are based on rawins at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), May 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.